Oceanus

REPORTS ON RESEARCH AT THE WOODS HOLE OCEANOGRAPHIC INSTITUTION

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Ocean Engineering & Technology 1995

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An array of mooring flotation awaits anchoring. UPPER OCEAN PROCESSES GROUP

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WOODS HOLE OCEANOGRAPHIC INSTITUTION 1930

Editor: Vicky Cullen • Designer: Jim Canavan

Cover: *Al Duester attaches a tracking line to* ABE *during pierside testing in Woods Hole.* PHOTO BY AL BRADLEY

Ocean Engineering & Technology 1995

Extracting knowledge from the ocean is a difficult business. Salt water corrodes, winds make the sea surface rough riding for oceanographic vessels and moorings, and most of the time tool designers can't see their instruments while they're operating. Oceanographers have to remember to take everything they could possibly need with them to deploy a new instrument because the stockroom may be hundreds or even thousands of watery miles away. Oceanographic tools generally take many years to reach full operating capacity. And sometimes, just when the instrument is reaching maturity, a cable parts and an expensive prototype is lost—see Peter Wiebe's BIOMAPER tale on page 17.

Prototype oceanographic tools are usually one-of-a-kind, and tinkering to improve them goes on for the initial instrument's lifetime. Later versions may be off a manufacturer's shelf, but still the tinkering goes on and on. An ocean engineer's work is never really done: Data quality can always be improved or another measurement piggybacked on those being made.

An oceanographic instrument is conceived when a scientist begins to muse, "Now if we could just measure that property of the ocean or those several properties...." Bob Weller starts us off on this track (right) with a short discussion of the scientific value of deep-ocean moorings. The stories that follow touch on all the oceanographic disciplines. Together they demonstrate some of the trials and triumphs of Ocean Engineering and Technology, and bring you the state of the art in 1995.

Surface Moorings

Windows Above and Into the Water Column

Some 70 percent of the earth's surface is ocean. Its waters store and transport heat, fresh water, carbon dioxide, and other materials. Atmospheric circulation responds to change in earth's surface temperature, so if the ocean changes temperature or moves warm water from one location to another, the atmosphere responds. El Niño provides a dramatic example of how the ocean influences weather and climate: Changes in prevailing winds lead to an eastward shift of warm water in the equatorial Pacific that has wide-ranging climatic effects. (See *Oceanus*, Summer 1992, for a discussion of El Niño.)

We would like to know more about how the ocean gains or loses heat as well as fresh water, carbon dioxide, and other materials. Key questions are: What physical processes make these transfers across the air-sea interface? How does the thin surface layer of the ocean that is in contact with the atmosphere mix with the much larger volume of water below? How does the surface layer move properties across ocean basins?

To answer these questions it is essential that we measure both surface meteorology and ocean variability at the same time and in the same place. The sunlight at the sea surface is the source of heat. Evaporation, infrared radiation, and direct heat transfer remove heat from the ocean. To study these phenomena we need measurements of incoming shortwave and infrared radiation, air temperature, sea-surface temperature, the humidity of the air, and wind speed. Rainfall measurements help us determine the balance between precipitation and evaporation. Wind data help us examine the driving forces for surface currents and mixing in the upper ocean. To investigate the ocean's role in air-sea exchange, we need extensive information about ocean currents, temperatures, salinities, and chemical properties.

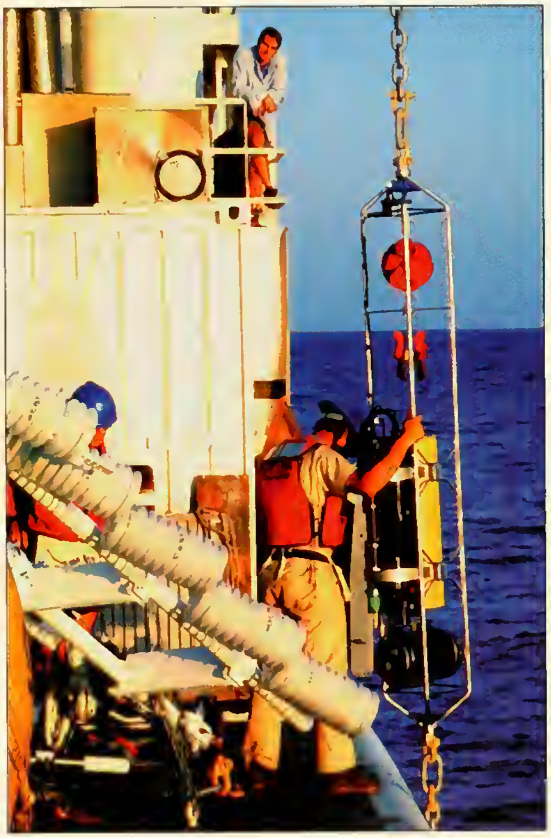

BOB WELLER

Photo of 1995 WHOI surface mooring deployment in the Arabian Sea shows one of many instruments on the line. Multivariable Moored System sensors like this one are collecting data for Lamont-Doherty Earth Observatory and University of Southern California scientists.

The only tool oceanographers have to collect coincident, long time series of surface meteorology and ocean properties is the surface mooring. The buoy carries the meteorological sensors, and the mooring line beneath it carries the oceanographic instrumentation. Development of the reliable, well-instrumented surface mooring at WHOI has provided the community of oceanographers with what may prove to be its most important tool for studying air-sea interaction. WHOI surface moorings have, in recent programs, supported instrumentation from US and international scientists interested in the acoustics, biology, and optics, as well as the physics, of the upper ocean. The surface meteorological sensor modules developed at WHOI for use on buoys also equip other institutions' buoys and many of the research vessels of the University-National Oceanographic Laboratory System.

—Bob Weller

Deploying A Typical Surface Mooring

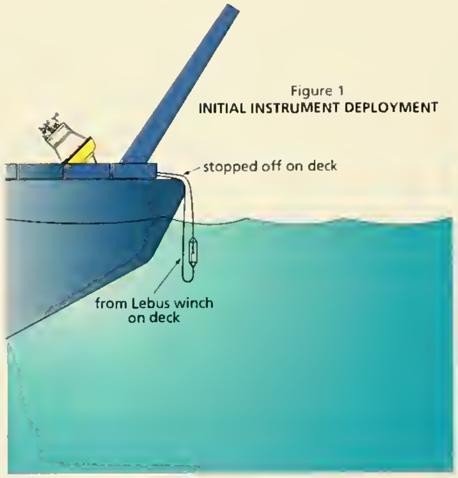


Figure 1
INITIAL INSTRUMENT DEPLOYMENT

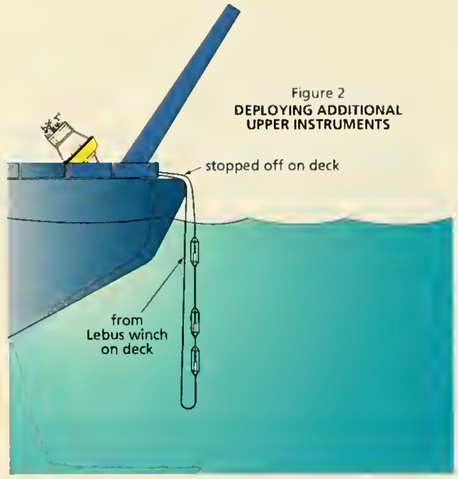


Figure 2
DEPLOYING ADDITIONAL UPPER INSTRUMENTS

Surface Mooring Technology

A Recent History

Richard P. Trask
Research Specialist, Physical Oceanography Department
Robert A. Weller
Senior Scientist, Physical Oceanography Department

Since the late 1970s there has been growing interest in understanding interactions between the ocean and the atmosphere. Pioneering projects such as the Joint Air Sea Interaction (JASIN) experiment in 1978 off the coast of Scotland and the Long Term Upper Ocean Study (LOTUS) off the East Coast of the US (1980–1984) required the surface mooring as a tool to study air-sea interactions.

Earlier attempts to use surface moorings met with mixed results (see following article), but JASIN and LOTUS proved the surface mooring's competence, and its capabilities have increased considerably over the past 15 years. Since its resurrection, the surface mooring has been used in many different locations throughout the world from benign, deep-water (as much as 5,500 meters) equatorial regions to shallow, dynamic coastal areas and deep-water sites swept by seasonal monsoons and high, Arabian Sea waves. With each application we learn new techniques and continue improvements. Still, fielding surface moorings in some locations remains an engineering challenge.

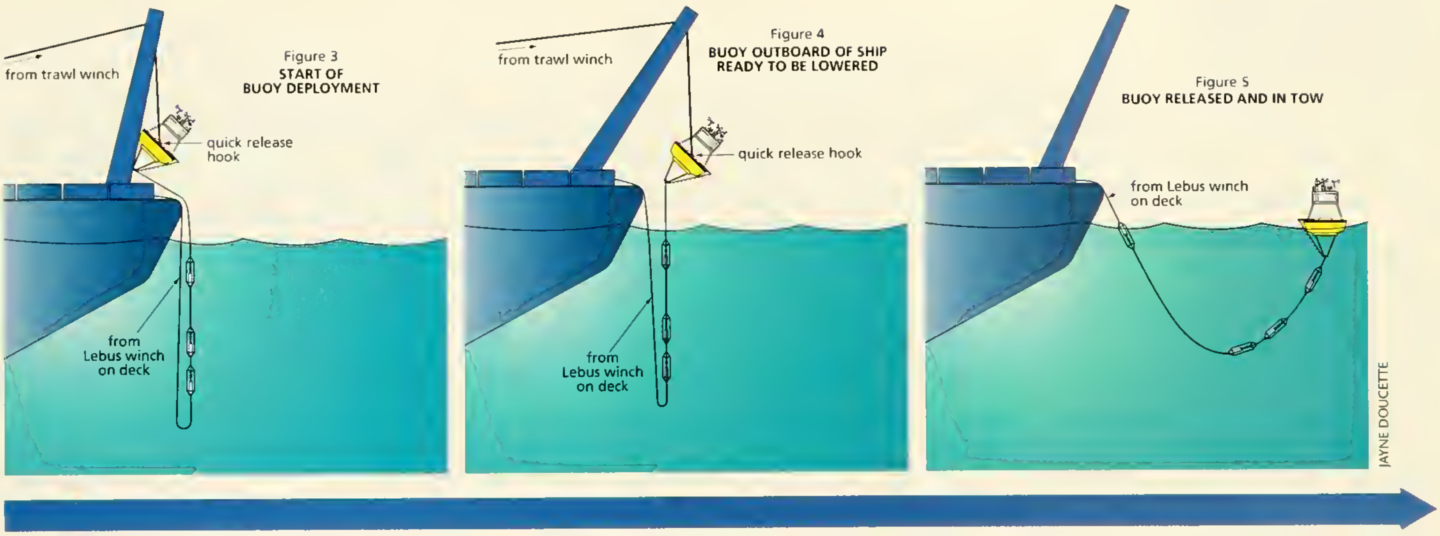
Surface mooring designers must consider the effects of surface waves, ocean currents, biofouling, and other factors that can vary with time of year, location, and regional climate and weather patterns. A successful deployment often hinges on our ability to accurately predict the range of conditions the mooring may encounter. The primary goal of any mooring deployment is to keep the mooring on location making measurements. Adverse environmental conditions not only influence the mooring longevity itself but also impact the instruments that the mooring supports. Keeping the instruments working under such conditions for long periods of time is often very difficult.

This article describes some engineering challenges that resulted in significant advances in surface-mooring technology over the past 15 years and offers a glimpse of some future designs that are on the drawing board or, more accurately today, the computer screen.

Modern Surface Mooring Designs

As the name implies, the surface mooring uses some form of surface buoy floating on the ocean surface. It has unique measurement capabilities. First, it can support submerged oceanographic instrumentation from very close to the surface (as shallow as .25 meters) to near the bottom, typically to 5 kilometers depth. The surface buoy also provides a platform for making meteorological measurements and a structure for telemetering both surface and subsurface data via satellite.

The surface buoy comes in a variety of shapes, including the toroid or "donut," the discus, and the hemispherical hull. The Upper Oceans Processes Group at WHOI employs the 3-meter-diameter discus buoy initially designed for LOTUS by Henri Berteaux and Robert Walden. With 4,500 kilograms (10,000 pounds) of buoyancy, the 3-meter discus buoy accommodates deep-water applications where a significant amount of instrumentation must be supported. The design has proved so



successful that the National Data Buoy Center in Mississippi now has 38 of these buoys available for use in coastal waters, at Great Lakes stations, and for directional wave measurements.

The buoy is kept on station with a combination of chain, plastic-jacketed wire rope, synthetic line, and a large cast-iron anchor. The figure on page 5 depicts a typical deep-water surface mooring. Just above the anchor there is an acoustic release and a number of glass balls. To retrieve the mooring, we trigger the release acoustically from the recovery vessel to disconnect the mooring from the anchor. The buoyant glass balls then bring the lower part of the mooring to the surface for recovery.

Engineering Challenges

The unique capabilities of the surface mooring are a direct result of having a buoy at the ocean surface—but this also presents many challenges when designing a surface mooring to survive at a particular location. The buoy moves with the surface waves and thus couples surface-wave motion to the mooring line below, subjecting the entire mooring to the fury of ocean storms, with associated high winds and waves. Subsurface ocean currents impose additional design challenges. Every surface mooring is different. Each is tailored specifically for its intended use, and we incorporate lessons learned from previous deployments into each one to maintain progress in extending the platform's capabilities.

The fact that certain fish bite mooring lines dictates the use of chain and wire rope in the upper part of the mooring. It is not uncommon to find cuts and nicks, as well as parts of teeth, embedded in mooring lines down to a depth of 2,000 meters. Wire rope is used in these parts of the mooring whenever possible since it is highly resistant to fish-bite damage.

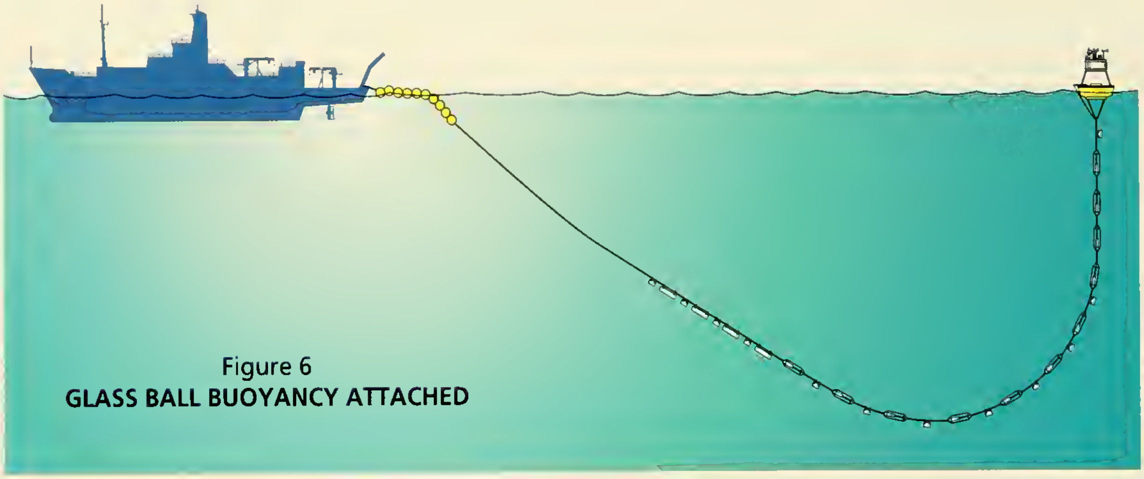
The surface mooring needs some form of built-in "compliance" (ability to stretch) to compensate for large vertical excursions the buoy may experience with passing waves and the drag forces associated with ocean currents. In deep-water applications, compliance is provided through the use of synthetic materials such as nylon: The synthetic line acts like a large rubber band that stretches as necessary to maintain the connection between the surface-following buoy and the anchor on the bottom. A challenge in the design process, particularly in shallower water, is to achieve an appropriate mix of compliant and stretchless, fish-bite-resistant materials.

The "scope" of the mooring—the ratio of the total unstretched length of the mooring components to the water depth—has historically been a very sensitive design factor. A mooring with a scope of less than 1.0 relies on the stretch of the nylon for the anchor to reach the bottom. Such a taut mooring remains fairly vertical with a relatively small watch circle (the diameter of the area on the ocean surface where the buoy can move about while still anchored to the ocean bottom), but it carries a penalty: Such a vertical mooring is under considerable tension, or

Will Ostrom signals the winch operator during the Arabian Sea surface-mooring deployment in the spring of 1995.

The eight figures above and on the two following pages show the sequence of a mooring deployment. The mooring line is paid out from a main deck winch (Lebus) during upper instrumentation deployment, then the dredge winch is used with a separate handling line to launch the surface buoy as the ship steams slowly forward. It takes about 6 hours to set a mooring and about 45 minutes for the anchor to reach the seafloor in 5000 meters of water. Once on site, the mooring generally collects data for six to eight months before it is serviced or replaced.

The mooring's surface buoy, designed for up to 10,000 pounds of buoyancy, carries a variety of meteorological instruments and telemetering equipment for transmitting data to laboratories ashore via satellite. Instruments located along the mooring line may include a variety of current meters and, depending on the investigators involved, sensors for temperature, salinity, dissolved oxygen, light, and zooplankton. The yellow spheres attached near the bottom of the mooring represent as many as 85 glass balls in plastic hardhats, each providing about 50 pounds of buoyancy, which bring the lower part of the mooring line to the surface for recovery once the acoustic release located just above the anchor is activated by surface command.



"preloaded," at the time of deployment. Currents and waves impose additional loads beyond the initial preloaded condition. The early LOTUS deployments used a scope of .95, and one surface buoy was lost. The final four LOTUS science moorings had a scope of approximately 1.05, and all were recovered. Moorings with scopes between 1.0 and approximately 1.1 are generally referred to as "semi-taut" designs.

Early surface moorings were designed using only a static analysis program with steady-state current profiles as input to predict mooring performance. Only recently, following a 1989 mooring failure south of Iceland, have mooring designers considered the combined effects of strong currents and surface waves. During that deployment, tensions below the buoy varied between 1,000 and 4,000 kilograms, at the period of the surface waves. Under this cyclic loading a 5/8-inch-diameter weldless sling link failed. Later tests verified that the sling link (see photo below) failed due to fatigue, and no evidence of flaws in the metal, such as entrapped inclusions, could be found.

WHOI UPPER OCEAN PROCESSES GROUP

Failure of a single component, like this weldless sling link from a mooring south of Iceland, can lead to overall mooring failure.

The desire to make moored surface and near-surface measurements in severe environments (such as in the Gulf Stream) and at high latitudes (south of Iceland, for example) prompted a reevaluation in 1990 of the semi-taut surface mooring design. We determined that mooring tensions for a semi-taut design grew too large when high currents were added to surface waves. High tensions limit the instrument-carrying capacity of the mooring and can lead to failed components. We then examined an alternative design fashioned after the National Data Buoy Center's "inverse catenary" mooring, and compared it with the semi-taut design. The inverse catenary design, with wire rope in the upper part of the mooring and nylon line spliced to polypropylene line below, offers larger scope (typically 1.2) for high current periods yet still performs well in lesser currents. In low currents the buoyancy provided by the polypropylene keeps the slightly negatively buoyant nylon from tangling with the rest of the mooring below it. Thus the inverse catenary design can tolerate a wider range of environmental conditions.

A second mooring deployed south of Iceland in 1991 was designed using both static and dynamic analysis. Part of the design process examined the dynamic response of the mooring to surface forcing. Since the tensions from the first Iceland mooring indicated a response to surface waves, the second mooring was tuned by adjusting the lengths of the wire and synthetic line so that the resonant response of the mooring was farther away from expected surface-wave frequencies. The inverse catenary design used for the 1991 mooring had a calculated resonant period (when taut) equal to 3.5 seconds, as compared to 5 seconds for the first mooring. The design changes, which included the inverse catenary design, the adjusted period of resonance, and a change in hardware size based on the fatigue tests, resulted in a successful deployment from April to September 1991.

With both the semi-taut and the inverse catenary surface mooring designs, it is difficult to make deep-

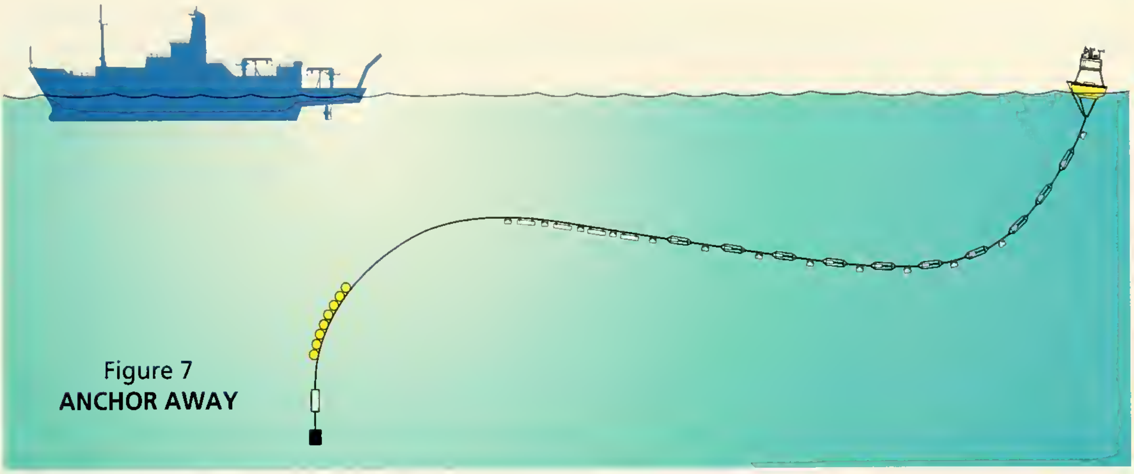


Figure 7
ANCHOR AWAY

current measurements because the mooring line at these depths is sometimes inclined greater than 15° from vertical. This is a problem because some instruments fitted with compasses do not work well if the compass is inclined more than 15°, and because some velocity sensors require the instrument to be vertical. Most instruments that measure the speed and direction of ocean currents, such as the vector-measuring current meter, are outfitted with a compass. An inverse catenary mooring with its greater scope has inclination problems at shallower depths than the semi-taut design. Hence the trade-off for being able to withstand a wider range of environmental conditions is a reduction in the depth range for making certain kinds of measurements.

Future Designs

The inverse catenary designs used between 1990 and 1995 for the Surface Wave Dynamics Experiment, the Subduction Experiment, the Marine Light in the Mixed Layer experiment, the Acoustic Surface Reverberation Experiment, the Tropical Ocean and Global Atmosphere-Coupled Ocean Atmosphere Response Experiment, and most recently in the Arabian Sea Experiment have proved successful. (Brief descriptions of these and earlier large-scale experiments appear on page 6.) However, the problems associated with mooring inclination make it difficult to instrument the entire water column. We are investigating innovative ways to make moored measurements throughout the water column with a single mooring. Refinements to the mooring and/or the instrumentation are necessary. Today's mooring must be tailored to the tried-and-tested instruments that are presently available and that will presumably continue to be in use for quite some time. However, future development of new instruments that are smaller, lighter, and more sophisticated will certainly influence future mooring designs.

Today's surface moorings do a fairly good job at making closely spaced (in the vertical) measurements near the surface. Due to the large scope of the inverse catenary mooring, the buoy tends to drift about in a relatively large watch circle. Therefore we lack the capacity to make closely spaced horizontal measurements and match the scale we resolve with the vertical measurements. This is because two inverse catenary moorings placed too close together might tangle.

Techniques to make measurements using a three-dimensional array are under consideration. As new, smaller, less-expensive instruments become available, we will be able to instrument a three-dimensional array, begin to address questions about the horizontal variability of air-sea interactions, and observe more closely some of the oceanic features those interactions produce.

The work described here has benefited from support of both the Office of Naval Research and the National Science Foundation. Results from experiments utilizing arrays of surface moorings are often reported in the Journal of Physical Oceanography, Deep Sea Research, *and the* Journal of Geophysical Research

One of Rick Trask's first tasks after arriving at WHOI in 1980 was to improve the performance of a temperature-recording device that was to be deployed on the first LOTUS surface mooring. Little did he know at the time that it was just the beginning of a long association with surface moorings. Much has changed since those early deployments, but Rick's concern for high-quality data from reliable surface moorings remains unchanged.

Bob Weller worked for an oceanographer during college while getting a degree in engineering and applied physics. In graduate school at Scripps Institution of Oceanography, he and his advisor, Russ Davis, developed the Vector Measuring Current Meter for use from surface moorings. Since coming to WHOI as a Postdoctoral Scholar in 1979, Weller's efforts have focused on understanding the physics of air-sea interactions and asking for new measurement capabilities from Rick Trask and the rest of the Upper Ocean Processes Group.

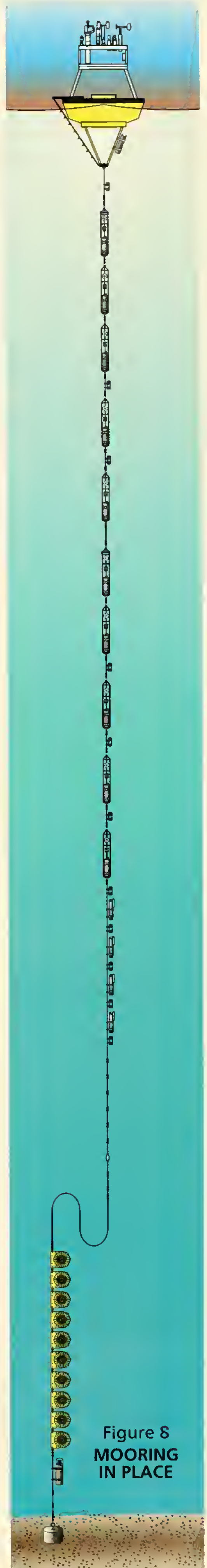
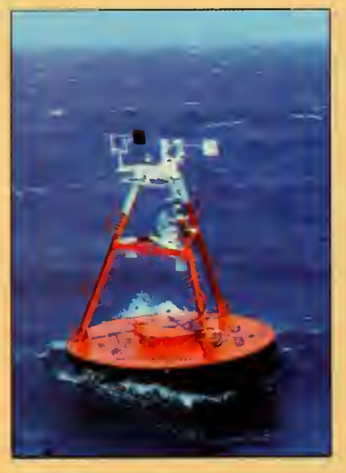


Figure 8
MOORING IN PLACE

AYNE DOUCETTE

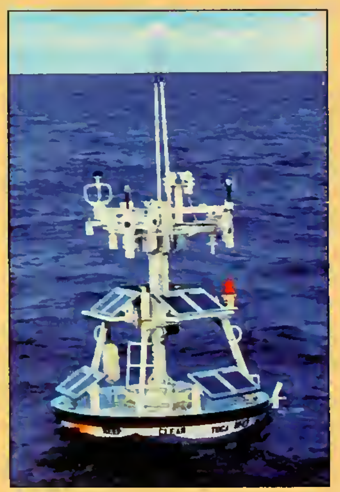
Moored Instrument Projects
1978–1995



LOTUS buoy

Joint Air-Sea Interaction Experiment (JASIN), 1978. A pioneering 60-day, multinational, air-sea interaction experiment conducted between Iceland and Scotland using ships, airplanes, and surface moorings. Its success at collecting the type of data needed to understand ocean-atmosphere coupling motivated much of the research that followed.

LOng Term Upper-ocean Study (LOTUS), 1980–1984. Pushed surface-meteorology and ocean-variability observation period to two years using surface and subsurface moorings. Though significant difficulties were encountered, particularly with winter deployments, four six-month, back-to-back deployments of surface moorings were carried out, and the LOTUS data set provided the community with important new information that led to significant scientific results.



TOGA-COARE buoy

Surface WAve Dynamics Experiment (SWADE), 1990–1991. The objective was to collect detailed information about the directional distribution of surface waves that are generated by the wind and can then propagate great distances across ocean basins. SWADE, designed to look at the physics of wave growth, propagation, refraction, and breaking, included an array of buoys to measure winds and waves off the coast of Delaware.

Subduction Experiment, 1991–1993. In "subduction," several physical processes carry surface water, which is in direct contact with the atmosphere, down into the interior of the ocean. An array of five surface moorings was deployed by WHOI and the Scripps Institution of Oceanography in a large, square array (with one mooring in the center). Its objective was to test the hypothesis that seasonal variations in surface meteorology and large-scale patterns in surface winds and heat fluxes over the eastern North Atlantic drive some of the processes that lead to subduction.

PHOTOS COURTESY UPPER OCEAN PROCESSES GROUP

Arabian Sea buoy

Marine Light in the Mixed Layer, 1991. Water mixed up from below into the surface layer carries nutrients that stimulate the growth of phytoplankton, including some that emit light. South of Iceland, the prevalence of fronts and eddies provides a likely setting for nutrient upwelling. A surface mooring equipped with meteorological sensors and instruments to measure bioluminescence as well as other optical, biological, and physical properties in the water column was deployed there to investigate the processes responsible for variability in phytoplankton populations.

Acoustic Surface Reverberation EXperiment (ASREX), 1991–1992. As waves break, they inject bubbles into the water. Most of these bubbles rise to the surface, but some very small ones (0.05 millimeter in diameter) stay suspended in the water. Clouds of bubbles can greatly reduce the speed of sound in the water (in some cases reducing it below the speed of sound in air). Although these bubble clouds are believed to be the main mechanism for scattering sound in the ocean, it is not yet clear how to predict their strength and structure. ASREX combined measurements of acoustic scattering from bubble clouds with measurements of winds, waves, and currents made from surface buoys.

Tropical Ocean Global Atmosphere-Coupled Ocean-Atmosphere Response Experiment (TOGA-COARE), 1992–1993. In the western Pacific, near the equator, a large region of the sea surface is warm, typically above 28°C. During El Niño, this warm water shifts eastward along the equator, toward South America. COARE sought to understand the physical processes that maintain the warm pool and how it influences the atmosphere at remote locations.

Arabian Sea, 1994–1995. In many parts of the world, the seasonal cycle of surface meteorology is characterized by warm, calm summers and cold, stormy winters. As a result, there is a shallow, warm surface layer in the ocean in the summer, and a deep, cool surface layer in the winter. In contrast, the surface layer of the Arabian Sea cools during the summer. The strong, sustained winds of the southwest monsoon may play an important role in cooling the surface layer, but the exact reason for the cooling is not known. It could be due to greater evaporative and sensible (conductive) heat loss at the sea surface in the high winds of the monsoon, or to wind-driven mixing in the ocean that brings up cooler water from below. A surface mooring has been deployed to collect data through both the winter and summer monsoons to improve understanding of mixed-layer physics in the Arabian Sea.

NICK FOFONOFF

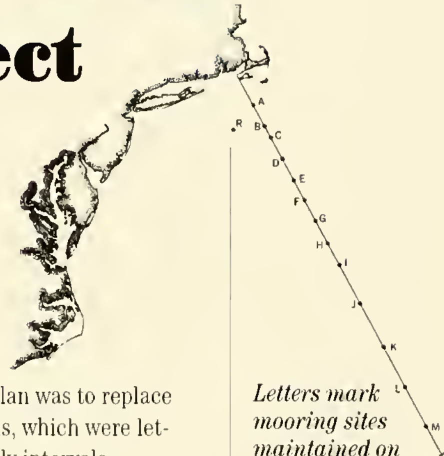
The Buoy Group launches a buoy during a 1967 R/V Atlantis II *demonstration cruise for Vice President Hubert Humphrey.*

The WHOI Buoy Project

Mooring Technology's Early Days

Bob Heinmiller
Internet Consultant

Nick Fofonoff
Senior Scientist Emeritus, Physical Oceanography Department



Letters mark mooring sites maintained on the Woods Hole-to-Bermuda line by the Buoy Project in the late 1950s and early 1960s. After that, the effort narrowed to sites D and L, which was shifted to 70°W, and a site near Bermuda.

The origins of present-day mooring technology go back 35 years. In the 1950s, observations with drifting floats convinced oceanographers that the deep ocean was far more energetic than they had previously thought. They needed new technology to measure deep currents in the open ocean.

In the late 1950s, Bill Richardson started a project at WHOI to measure currents at various depths by establishing several mooring stations along a line from Woods Hole to Bermuda. For surface flotation, he used a 10-foot-diameter fiberglass doughnut topped with a tripod that supported a small platform and antenna. Surplus railroad wheels were used as anchors. The polypropylene or nylon mooring line between the buoy and the anchor supported current meters at variable intervals from the near surface to the bottom.

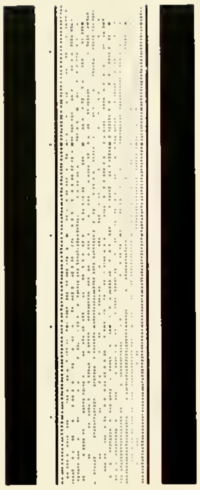
Setting a mooring involved launching the surface buoy and steaming slowly away while attaching the successive mooring components: rope, instruments, and finally the anchor. The anchor was attached by a corrosible weak link. When it came time to recover the mooring, pulling on the float was supposed to break the weak link, reducing the strain on the line. Unfortunately, the damaged line was often weaker than the weak link, resulting in the loss of the instruments.

The early current meters used a spinning turbinelike device called a Savonius rotor (developed in Finland in the 1930s for power generation) to sense the current speed. The data were recorded as arrays of dots on 16-millimeter movie film. The plan was to replace the moorings at each of the stations, which were lettered A through M, at about monthly intervals.

Richardson struggled with the technology for several years. Very few of the moorings lasted as much as a month on station, and where there were higher currents near the Gulf Stream the mortality was almost total. Even when moorings were recovered intact, the instruments frequently produced poor or no data because of mooring motion. The analog data (tiny white dots on a black field) created myriad processing and interpretation problems. At least some moorings were apparently lost to pirates—Richardson claimed to have seen one of his distinctive orange toroidal surface floats on the deck of a Russian trawler.

By the time he left WHOI in 1963, Richardson* had pushed the technology about as far as it could go. The Buoy Project, as it had come to be known, was taken over by Nick Fofonoff and Ferris Webster. The people who worked on the Buoy Project became known as the Buoy Group. For the next few years, several efforts were pursued in parallel. One was to diagnose the failures of the Richardson mooring design. A suspected mode of failure involved attacks on the synthetic rope mooring lines by fish. After collection and careful analysis of broken lines salvaged by tracking down buoys that had gone adrift, Paul Stimpson and Bryce Prindle showed that lines were being bitten primarily by one species of fish, which was apparently trying to eat drifting copep-

* Bill Richardson left WHOI in 1963 for the University of Miami, and then moved to Nova University (in Ft. Lauderdale) in 1965. In January 1975, he was lost aboard the small research vessel *Gulf Stream* in the Gulf of Maine, where he was testing expendable, drogued, satellite-tracked buoys to monitor surface currents and other parameters in severe environmental conditions.



Early current-meter data were recorded as dots on 16-millimeter movie film—the first digital records of oceanographic data. In various combinations, the 19 tracks of information on the example above record rotor revolutions, compass readings, vane direction, and magnetic information. Good quality films like this one could be read by machine—an 18-hour process for a 100-foot film (which contained 200,000 current vectors). Blurred or light-struck film had to be read by eye and the dots and spaces keypunched as ones and zeros into computer cards, usually several thousand cards for an instrument deployment.

ods caught on the lines. The clincher was finding distinctive teeth embedded in the polypropylene jacket of test mooring wires. The fish-bite problem only occurred relatively near the surface, but dictated the use of wire rope at least in the upper 1,500 meters of the moorings.

A related effort went into the development of subsurface moorings, that is, moorings whose primary flotation was just below the surface, avoiding entirely the highest stress part of the water column, the wind and wave action near and at the surface. However, subsurface moorings awaited the development of two additional pieces of technology: wire rope and the remote acoustic anchor release. In addition to protection from fish bite, subsurface moorings required a nonelastic mooring line so that the subsurface flotation could be positioned precisely. Henri Berteaux and Bob Walden conducted an elaborate testing program to choose the best wire rope for the job, and they also developed fittings or terminations for the ends of the wire rope that could be applied in the lab or aboard ship to take the full strength of the wire while providing corrosion protection. (Part of the wire rope testing involved a "buoy farm" in Vineyard Sound. One of the 1.5- meter-diameter buoys broke free and was hauled ashore by an enterprising Vineyarder, who refused to give it up and buried it in his back yard. The buoy was eventually returned, after the individual was contacted by the FBI about missing US government property.)

NICK FOFONOFF

Early backup flotation (glass balls in nets) began to allow recovery of moorings whose lines had failed. This recovery is aboard R/V Knorr *in 1970.*

The development of a remotely operated, acoustically commanded anchor release and backup recovery floatation was key to the entire effort. Even with surface moorings, the ability to drop the anchor before attempting to haul the instrument string would drastically improve the odds of retrieving the instruments on a possibly damaged mooring that had survived many days at sea. The acoustic releases were developed both by Ocean Research Equipment, Inc. in Falmouth, Massachusetts, and by AMF Corporation of Alexandria, Virginia, with close participation by Buoy Project personnel in specification and testing.

WHOI BUOY PROJECT

When a mooring line failed, it sometimes became a hopeless tangle that came to be known as a "wuzzle." Here Buoy Group members Bob Heinmiller, right, and Jim Gifford retrieve a wuzzle.

While the engineering effort was under way, the operational program continued, attempting to do as much science as possible while the engineering proceeded. The Woods Hole-to-Bermuda line was scaled back to one or two stations. Station D, in particular, became a familiar patch of ocean to the Buoy Project seagoing teams.

Meanwhile, however, the recovery rate on moorings was unacceptable. The low point came in August 1967, when a decision was made at sea not to set the new batch of moorings since almost none of the previous month's deployment had been recovered. For the first time in eight years, no WHOI moorings were monitoring the Cape Cod-to-Bermuda line.

However, within a year or two, engineering improvements renewed confidence in the mooring system. A critical development during this period was the formation of a highly trained team of people with standard tools and procedures to carry out the lab and at-sea operations.

While the Buoy Project was struggling with the mooring technology, a parallel effort was under way to improve the instrumentation. A new current meter developed in cooperation with Geodyne Corporation recorded on magnetic tape in digital format. Also, instrumentation was expanded to measure temperature, instrument depth, and other parameters. (An early version of a

multisensor digitizing package was named the Lowered Sensing Digitizer. We soon found that in the late 1960s it was not good to chat over the ship-to-shore radio about "how the LSD was holding up!" The problem was solved when the prototype was lost at sea and superseded by a package with a less provocative acronym.)

By the early 1970s, the technology had come of age. Moorings were being routinely deployed for up to a year. The new capabilities made it possible to mount the large scale MODE (Mid-Ocean Dynamics Experiment, 1971 to 1973) and POLYMODE (Joint US-USSR experiment, 1974 to 1980) programs that were centered around the use of moored instruments. (During MODE, mooring piracy reared its head again. The radar of one of the MODE research ships indicated a large vessel lurking near the central surface mooring. When it steamed away, the mooring was gone.) During the 1980s and into the 1990s, the technology continued to improve as new materials and electronics became available.

A new type of mooring (called the "intermediate mooring," because some of the buoyancy was at intermediate depths), with glass-sphere buoyancy distributed over the entire length of the mooring, provided a higher degree of reliability than the single-point shallow buoyancy of the subsurface mooring. Kevlar, a then-new synthetic material from Dupont with characteristics similar to steel, opened up new possibilities. New sensors and recording capabilities expanded the range of parameters that could be monitored.

During this period, there were deep-sea mooring projects at other US institutions, including the Scripps Institution of Oceanography, Florida State University, and the University of Oregon at Corvallis. Russian, British, and French laboratories also carried out work in this area. However, with strong funding support from the Office of Naval Research (ONR) and the National Science Foundation (NSF), the WHOI Buoy Project became the primary site for development of new mooring technology, which then spun out to other groups.

As the problems of mooring survival were solved and the scientific applications diversified, the purpose and structure of the Buoy Project needed to be changed. The effort could now be concentrated on using the technology in specific scientific programs.

NICK FOFONOFF

The heavier line in this photo was used by "pirates" trying to recover a mooring. They took the surface buoy and broke the thinner mooring line in the process.

NICK FOFONOFF

An R/V Knorr *cruise recovered moorings in the Gulf Stream Extension array east of the Grand Banks in November 1980.*

Bob Heinmiller joined the WHOI Buoy Project in 1964 following completion of a bachelor's degree at MIT and a stint in air-sea interactions at WHOI. He managed the shop and seagoing operations for the project from late 1966 until 1976, when he returned to MIT, where he managed the US office of the US-USSR POLYMODE program. In 1980, with Susan Kubany, he co-founded Omnet, Inc., which ran SCIENCEnet, a pioneering communications and information network for earth scientists until the end of 1994. Currently, he consults on the World Wide Web and computer systems for businesses.

Nick Fofonoff first came to WHOI as a graduate student in the summer of 1952. A year in England and several in western Canada followed before he returned to join the WHOI scientific staff in 1962. Bill Richardson's departure in 1963 created a crisis for the Buoy Project that was resolved by Henry Stommel and Arnold Arons persuading Fofonoff and Ferris Webster to take on its operation—a commitment for Fofonoff that was to last over two decades. The move from theoretical oceanography to engineering was daunting, but Fofonoff thinks his early exposure to machinery on a farm in Alberta helped ease the transition.

Editor's Note: Author Heinmiller will receive the American Geophysical Union's Ocean Sciences Award at the organization's 1995 fall meeting "for developing an electronic mail system for the oceanographic community that has dramatically changed our discipline. He and Susan Kubany bravely led the way for oceanographers to enter the electronic mail era well before e-mail was popular."

Visualizing the Deep Sea

Vehicles and Research Techniques Yield Ever-Clearer Images of the Ocean Depths

Daniel J. Fornari
Associate Scientist, Geology & Geophysics Department and Chief Scientist for Deep Submergence
Andrew D. Bowen
Research Engineer, Applied Ocean Physics & Engineering Department
Dudley B. Foster
Research Associate, Applied Ocean Physics & Engineering Department

Since the late 19th century, scientists and naturalists have been trying to solve the mysteries of the seafloor and the vast, watery "inner space" of the ocean depths. Because of these realms' remoteness and harsh physical setting, researchers have had to rely on a variety of ingenious tools to further their understanding of fundamental physical processes in the ocean environment.

The history of deep-sea investigations is quite short. The first glimpses of the ocean floor were bits of mud and an occasional creature brought to the surface on the ends of sounding, or depth-gauging, lines in the early 1800s. The earliest extensive data on deep-sea life was gathered on the British *Challenger* Expedition (1872–1876). Sound echoing from the seafloor was first used to measure the depth of the ocean in 1920, and a remotely triggered camera brought back the first image of a tiny portion of the seafloor in 1939. (In those days, a camera was lowered to make a single photograph and then raised to the ship for reloading.) Precision depth recorders, which draw bottom contours using data from repeated pulses of sound reflected by the seafloor and layers of sediment and rock beneath it, made their debut in 1954. The deep submergence vehicle *Alvin* was placed in service at the Woods Hole Oceanographic Institution (WHOI) in 1964, offering scientists the opportunity to routinely observe deep-sea phenomena with their own eyes.

Since then, the technology that scientists can bring to bear on the increasingly process-specific studies of geological, chemical, and biological phenomena in the deep sea has advanced tremendously. In the last two decades, the deep-submergence research community has revolutionized the marine sciences by making significant discoveries using innovative technology and multidisciplinary field studies. The discoveries include the identification of volcanic and hydrothermal processes at mid-ocean ridge crests in different geographic settings and tectonic environments, and the presence of previously unknown, abyssal biological communities with a rich diversity of species that are sustained by chemosynthetic processes derived from hot hydrothermal vents rather than the photosynthetic process that sustains most life on land. In addition, scientists have identified a vast number of new animal species that comprise the enormous mid-water-depth biomass. The isolated snapshots and short-term, deep-ocean observations of early bottom cameras and bathyspheres have been replaced by much longer observations at, or near, the seafloor. Observational, optical, and acoustic data are now routinely acquired using modern deep-diving submersibles such as *Alvin*, towed instrument packages, and sophisticated remotely operated vehicles (ROVs).

For the past 10 years, *Alvin* (whose depth capability is 4,500 meters) has consistently logged more on-bottom hours than any of the other deep-diving

PATRICK HICKEY AND ROBERT GRIEVE, ALVIN GROUP

The red laser beams in the photo at right come from four small laser units mounted around the new 3-chip, high-resolution color video camera on Alvin. *Three of the red dots that appear in the center of the inset photo are spaced 12 inches apart, and the fourth laser dot is offset. The amount of offset allows scientists to geometrically correct for distances in different portions of the photograph in order to accurately measure the tube worms or features on the lava rocks at the bottom of the photo.*

submersibles available to the worldwide scientific community. The other currently operating deep-diving submersibles include the US Navy-operated *Sea Cliff* (6,000 meters) and *Turtle* (3,000 meters); *Pisces V* (2,012 meters) operated by the University of Hawaii; the French *Nautile* (6,000 meters) and *Cyana* (3,000 meters); Japan's *Shinkai 2000* and *6500*, whose numerical names indicate their depth capabilities; and the Russian *Mir 1* and *Mir 2* (both 6,000 meters.)

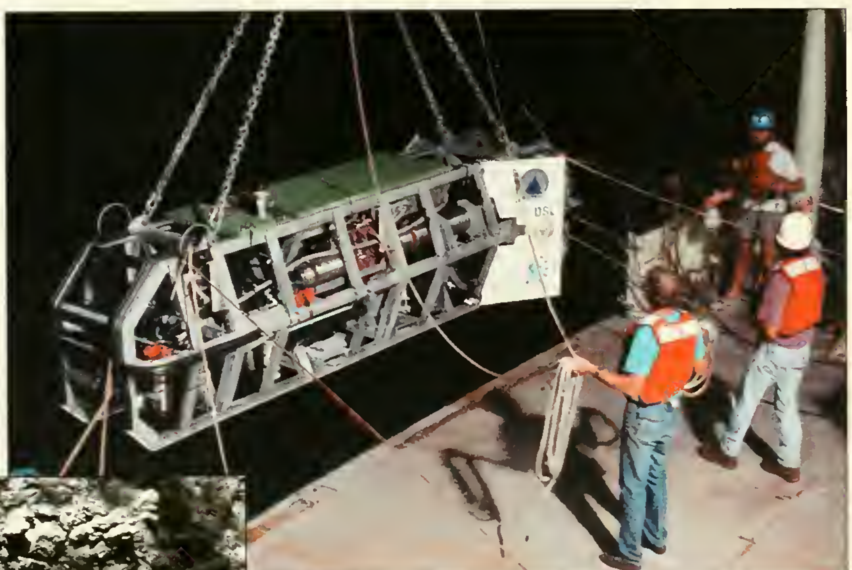
Over the past few years *Alvin's* imaging equipment has been upgraded significantly to include a high-resolution, color video camera; scaling lasers for quantitative measurement of objects in still and video images; metal-halide, deep-sea lighting for wider-area observation and improved video imaging; and a 675-kilohertz scanning altimetric sonar for seafloor mapping with a vertical resolution of about 10 centimeters. The metal-halide lighting and high-resolution color video cameras provide a significant increase in the clarity and color balance of seafloor imagery compared to older cameras and lights that did not have their resolving power, low-light characteristics, color spectrum, and light-transmission properties. In the past, dimensions of features in both video and still photographs taken from *Alvin* had to be inferred. Now, with the standard use of laser scalers, small red dots, a known distance apart, appear in the imagery and can be used by scientists to quantify the size of objects on the seafloor. The scanning altimeters used on *Jason*, *Argo-II*, and *Alvin* permit a heretofore unprecedented ability to acquire a swath of very precise altimetric data several tens of meters wide for the seafloor to either side of a bottom traverse. All these new technologies vastly improve our ability to image, record, and understand the detailed character of the deep ocean floor. (For a glimpse of *Alvin's* earlier history, please see the inside back cover.)

The past 10 years have also seen a blossoming of ROV technology that has many applications for the offshore marine industry and deep-sea research. WHOI has been a leader in developing ROV and towed-vehicle technology for scientific and applied engineering studies. Much of this work has been under the leadership of Robert Ballard and funded by the Office of Naval Research. The *Jason* ROV, the *Argo-II* optical/acoustic imaging system, and 120-kilohertz sonar towed vehicles, all operated by WHOI for the scientific community, represent the latest in remote-sensing technology for worldwide study of the deep ocean and seafloor. They are poised to replace the older types of remote imaging systems that include simple cameras towed on a steel cable behind a ship.

ROVs like *Jason* can now make detailed multidisciplinary surveys of 1- to 10-square-kilometer areas on the sea bed or in the water column. *Jason* can maneuver, survey, and delicately sample at depths as great as 6,000 meters while maintaining navigational precision on the order of centimeters. The *Argo II* and 120-kilohertz sonar systems survey much larger areas of seafloor with unprecedented resolution. For instance, the 120-kilohertz sonar can map a 200-square-kilometer area in only seven days of continuous opera-

MAURICE EWING, ALLYN VINE, AND J. LAMAR WORZEL

This photograph, among the earliest seafloor photographs taken in water deeper than that accessible to waders or divers, shows sand ripples on Georges Bank, where the photo stations ranged in depth from 38 to 152 meters. It was taken with a free-floating, ballasted apparatus on R/V Atlantis *cruise 48 in June 1940.*

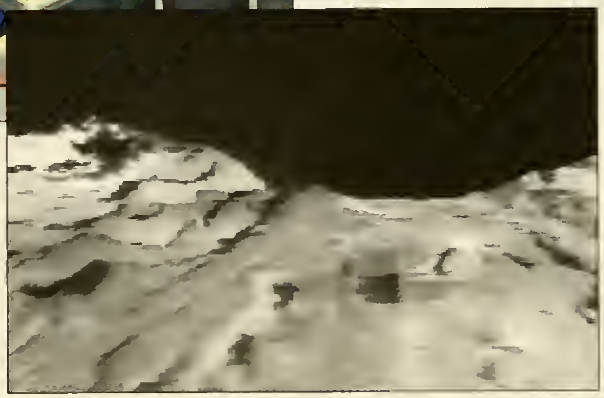


MARGARET SULANOWSKA

S. HUMPHRIS AND M. KLEINROCK

Argo II *comes aboard R/V* Knorr *following a 1994 survey of the Transatlantic Geotraverse (TAG) site on the Mid-Atlantic Ridge. An* Argo II *digital electronic still-camera image (inset) shows small (about 1 meter high) hydrothermal chimneys on the upper terrace of the TAG mound, one of the largest and best studied hydrothermal features. Such electronic still-camera images can be digitally mosaicked to create large-area, high-resolution photographic maps of the seafloor.*

MARGARET SULANOWSKA



KEN STEWART

The 120 kilohertz sonar system comes aboard R/V Knorr *following a survey. Acoustic data produced by this system includes reflectivity and meter-scale seafloor bathymetric contours that are used to make maps like the one inset, which shows an approximately one-kilometer-square area of the Juan de Fuca Ridge.*

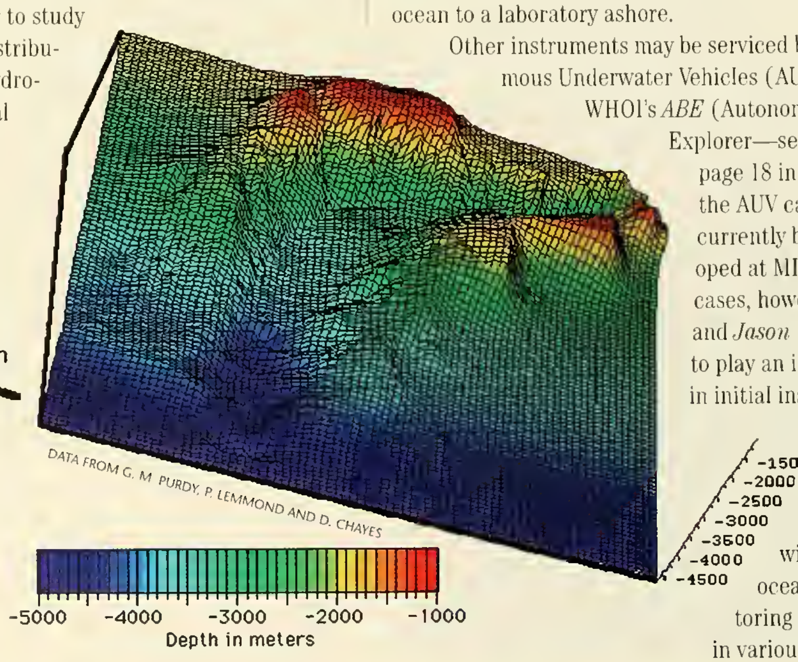
tion, acquiring full coverage of coincident acoustic backscatter and bathymetric data with vertical and spatial resolutions of about 1 meter.

Acoustic backscatter provides a sonar image of the seafloor that is much like an aerial photograph and permits the structural fabric of the terrain to be mapped; the bathymetry lends three-dimensional relief to the data. *Argo II* is equipped with cameras and sonars similar to those mounted on ROV *Jason*. Unlike *Jason*, which generally operates within about 10 meters of the bottom, *Argo II* is configured for a "high-altitude" (10 to 20 meters above the seafloor) mission, combining sonar, video, and other advanced imaging devices to give clear images of large areas. *Argo II* is often used by scientists to gain a regional perspective on the shape and structure of the topography, or to study the broader-scale distribution of geological, hydrothermal, or biological features.

Scientists are increasingly using a "nested" strategy for studying the deep sea. This concept uses, in successive field programs, instruments whose scale of data resolution increases at each stage, sometimes by an order of magnitude, resulting in more accurate perspectives of the physical setting or processes being studied. For a marine scientist trying to understand the topography and tectonics of a portion of seafloor, the first stage usually includes bathymetric mapping using ship's-hull-mounted, multibeam sonars, such as the Sea Beam 2100 system currently installed aboard R/V *Knorr.* The resulting maps provide large-scale (areas covering hundreds to thousands of square kilometers) perspectives of features on the seafloor at a vertical resolution of 10 to 20 meters. The 120-kilohertz sonar and *Argo II* vehicles can then provide the next level of investigative resolution, acoustic maps and photographic images that depict animals and terrain features at scales ranging from centimeters to about 10 meters. *Alvin* and/or ROVs such as *Jason* then allow observation and data collection at the finest scale of resolution for seafloor properties, imaging, mapping, and instrument manipulation.

To better understand the temporal component of many processes occurring at or near the deep seafloor, scientists are now developing sophisticated instrument packages to be deployed for periods of time that range from months to years. Examples include time-lapse cameras and temperature arrays, seismic-monitoring equipment, ground-deformation monitors, fluid-pressure monitors, chemical scanners, and near-bottom physical oceanographic arrays. Some of the instruments in these ocean-floor monitoring systems can be configured to transmit the acquired data via acoustic modem to the surface, where it can be obtained by a ship, or retransmitted via satellite from a buoy in the middle of the ocean to a laboratory ashore.

Other instruments may be serviced by Autonomous Underwater Vehicles (AUVs) such as WHOI's *ABE* (Autonomous Benthic Explorer—see article on page 18 in this issue), or the AUV called *Odyssey* currently being developed at MIT. In most cases, however, *Alvin* and *Jason* are expected to play an important role in initial installations of instrument packages associated with future ocean-floor monitoring systems and in various aspects of

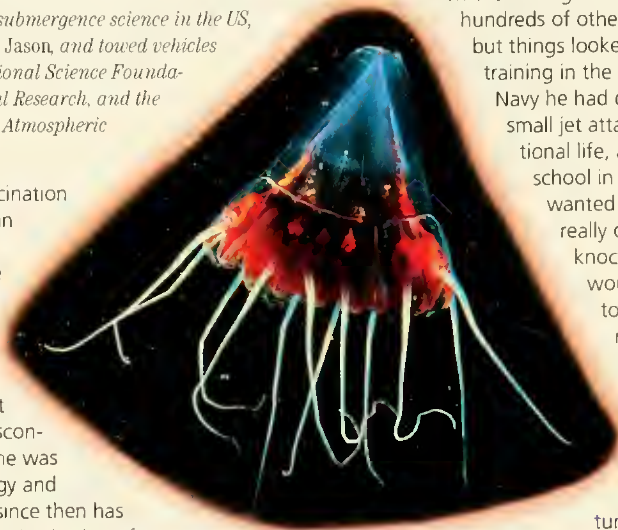


This perspective image of Perth Canyon, off western Australia was created from gridded bathymetric data (150-meter grid interval), acquired by the Sea Beam 2100 system installed on R/V Knorr.

their maintenance and continued operation.

Seafloor science has come a long way in the 120 years since the *Challenger* Expedition. Over the next five years and into the 21st century, we anticipate important roles for the vehicles and other tools described as we seek to further understand Earth's inner space, and explore the linkages between geological, chemical, and biological processes in the deep sea.

Funding for deep submergence science in the US, and support for Alvin, Jason, *and towed vehicles is provided by the National Science Foundation, the Office of Naval Research, and the National Oceanic and Atmospheric Administration.*

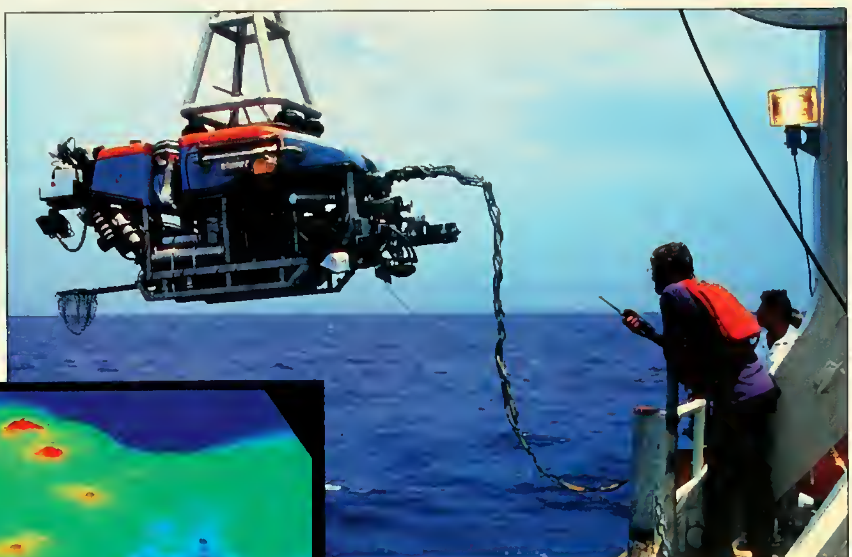


Studies of mid-water animals like this gelatinous medusa, Periphylla periphylla, *a species that ranges from 10 to 15 centimeters high, depend upon submersibles and remotely operated vehicles because they live below 500 meters and cannot be collected alive or intact by nets. The vehicles allow direct observation of the animals and specialized collection techniques.*

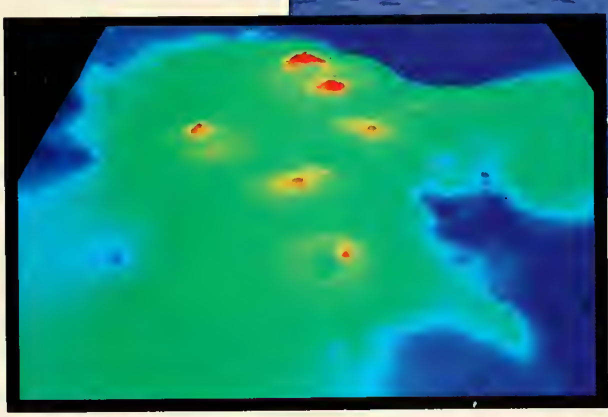
Dan Fornari's fascination with the ocean began when he was about eight years old while exploring the beaches on Shelter Island, off Long Island, NY. He went to school at the University of Wisconsin-Madison where he was introduced to geology and oceanography, and since then has worked at the Scripps Institution of Oceanography as a technician, and at the Lamont-Doherty Geological Observatory (where he earned his PhD in 1978) as a student and researcher. He took his present position at WHOI in 1993. His research focuses on volcanic and hydrothermal processes at mid-ocean ridges and the tectonics of oceanic transforms.

Andy Bowen has been involved in the rapidly changing world of remotely operated vehicles for over 15 years. Trained as a mechanical engineer, he joined the Institution in 1985 as a member of Robert Ballard's Deep Submergence Laboratory team, and quickly became involved in the design of *Jason Jr.* After a successful survey of RMS *Titanic* by Alvin and *Jason Jr.*, work began on the design of the *Jason* vehicle. Bowen assumed responsibility for the *Argo-Jason* development program in 1988. As the only remotely operated vehicle designed specifically for scientific operations to 6,000 meters depth, *Jason* has now become part of the National Deep Submergence Facility maintained and operated by WHOI. As manager of the remotely operated vehicle portion of this facility, Bowen's present challenge is to facilitate wider acceptance and understanding by the scientific community of robotic systems as research tools.

As a new, young, mechanical engineer, Dudley Foster worked for a short time as a weight and balance engineer on the Boeing 737. Sharing an acre-size office with hundreds of other engineers left much to be desired, but things looked up when he started Navy flight training in the late 1960s. When Foster left the Navy he had qualified in the A4 Skyhawk, a small jet attack aircraft. He liked a less-conventional life, and thought of going to graduate school in ocean engineering, but first wanted a real taste of what those folks really do in the ocean. In 1972 he knocked on WHOI's door. Anything would do, he told his interviewers, just to get some exposure. *Alvin was just* returning to service after the refit that followed its being sunk for a year, and he was hired as a liaison engineer to help scientists interface their equipment to the sub. Within weeks, he was at sea with *Alvin*, and, as it turned out, on the threshold of a new "age of discovery" in the deep sea. Project FAMOUS was his first working cruise as an *Alvin* pilot, and he has played a role in all of the major deep submergence discoveries, including the first look at the biological communities at the Galapagos Rift, the hot hydrothermal vents at 21°N on the East Pacific Rise (EPR), and the first witnessed submarine eruption on the mid-ocean ridge at 9°50'N on the East Pacific Rise. Needless to say, he never made it back for that ocean engineering degree, but what an adventure it has been!



GARY JAROSLOW



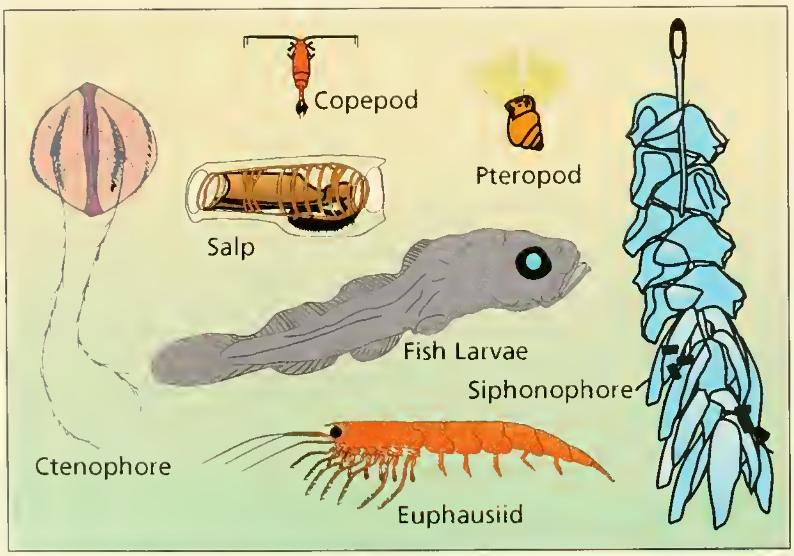
KEN STEWART

The remotely operated vehicle Jason *is launched from R/V* Knorr *during a survey of the Mid-Atlantic Ridge. An advantage of ROVs is their ability to shorten time-consuming tasks such as detailed mapping. Inset shows a high-resolution relief map of a 250-meter-square hydrothermal vent complex in the Guaymas Basin.*

Developing a High-Frequency System To Remotely "See" Plankton Distributions

Peter Wiebe
Senior Scientist, Biology Department

The marine planktonic animals that inhabit the world's oceans are mostly small (less than 50 millimeters long), but they come in many different shapes, and their bodies are composed of a variety of materials. There are gelatinous jellyfish and salps, snails such as shelled or shell-less pteropods, and exoskeleton encased crustaceans such as copepods and krill. Moreover, while their distributions worldwide are shaped by the major current systems and water masses, many are mobile enough to migrate hundreds of meters vertically with the rising and setting of the sun, creating zones of large change in abundance, known as "patchiness," both vertically and horizontally. The smaller-scale patchiness, especially in the horizontal, creates a fundamentally difficult sampling challenge for studies of the larger biogeographic distributions of the species that make up the plankton. Past studies have shown that the variability in abundance can be as great in the vicinity of a particular station as exists within a much larger area being surveyed by many stations. So how can the larger distributions be quantified unambiguously if smaller-scale variations are of the same order of magnitude? Attempts to study the patchiness itself present similar challenges.



Drawings of several different zooplankton types illustrate the wide range of body forms that the acoustic models must be able to characterize.

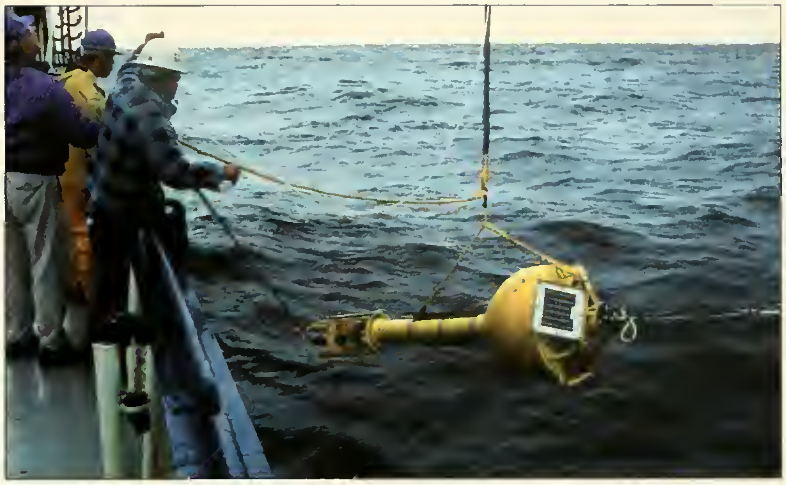
The conventional methods and gear available for sampling the vast reaches of the oceans provide samples that are relatively few in number and time consuming to process. As a result, the ocean interior is grossly undersampled both in time and space. We need new technology for collecting automated, high-speed, high-resolution data to allow the development of continuous three-dimensional images of plankton distribution on both small and large spatial scales. With it, we could better grasp the nature of the distribution and abundance of the ocean plankton and determine how they are coupled to their physical/chemical environment. We began to explore the use of high-frequency sound to meet this need several years ago. The investigators involved include WHOI staff members Tim Stanton and Dezang Chu, MIT/WHOI Joint Program student Linda Martin, Charles Greene (Cornell University), and the author.

The ocean, while largely opaque to visible light, is highly transparent to sound, especially low-frequency sound (below 1 kilohertz). That is, it can be used to "see" into the ocean interior for large distances. From a given location at sea, a high-energy sound source (a transducer) can be used to emit a narrow band of low-frequency sound. This sound energy will travel away from the source as an acoustic wave at about 1,500 meters per second, spreading as it goes. Particles in the path of the wave, which are mostly plankton, will reflect a small part of the sound energy back toward the transducer, creating an echo. The pattern of these echoes returning to the transducer as a function of time can be used to create an image of the "targets" present in the water column. But low-frequency sound cannot resolve animals as small as plankton. On the other hand, high-frequency sound in the range of 100 to 1,000 kilohertz can effectively resolve individual plankton, even though the range (tens of meters to over one hundred meters) at which this can be done is substantially shortened (compared to lower frequencies) as a result of absorption and scattering of the sound energy by elements in seawater.

Part of the attraction of using sound was the widely held assumption that the strength of the echo from an individual animal (the target strength) was largely dependent upon its size and little else. In the course of testing this assumption through experimental studies

with single living planktonic animals, however, we have discovered that the existing paradigm for how sound reverberates from the bodies of plankton is in strong need of revision. Although they may be similar in size, depending upon the material properties of their bodies (for example, gelatinous versus shelled), the echo energy can be hundreds, even thousands of times different. A single, hard-shelled pteropod can echo back as much energy as 10,000 or more copepods the same size. This obviously increases the difficulty of using sound to estimate the biomass or size of animals in the sea. Instead of a single frequency, we have turned to the use of several to many frequencies to characterize the reverberation from these animals. In the process, we are learning that different planktonic types have different acoustic "signatures," and we hope they will prove to be sufficiently unique to form the basis of new techniques for estimating biomass and size. In addition, the data from the experimental studies have given rise to several new mathematical models that can be used to predict volume backscattering from specific plankton types.

While the theoretical and experimental work is proceeding both ashore and aboard oceanographic research vessels, the development of instrumentation to study the distribution of plankton using high-frequency sound is also moving forward. Our efforts are twofold: development of an autonomous, free-drifting, or tethered system and concurrent development of a towed instrument package for rapid surveys of an ocean area. The equipment development was spearheaded by Ken Prada and Tom Austin.

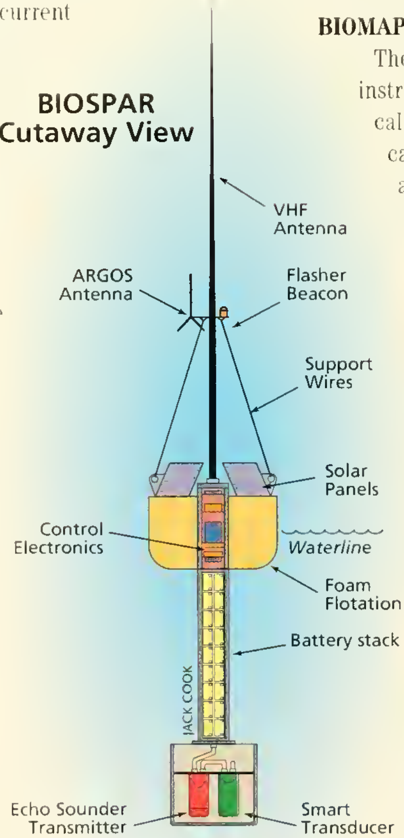

PETER WIEBE

BIOSPAR is launched in the Gulf of Maine from R/V Oceanus *in October 1993.*

BIOSPAR

We call our free-drifting acoustic system the BIOacoustic Sensing Platform And Relay (BIOSPAR). The modular design consists of a two-frequency, dual-beam echo sounder, a digital signal processor, mass storage, and a satellite and radio communication system mounted in a spar (pole) buoy. It collects high-frequency (120 and 420 kilohertz) backscattering information from the upper 50 to 100 meters of the water column in remote locations and relays it to a ship or shore location in real time. BIOSPAR can detect individual targets down to less than –90 decibels (plankton about 3 millimeters long). From the acoustic information BIOSPAR provides, in combination with net collected plankton taxonomic data, we can estimate zooplankton biomass, density (numbers of targets per volume of water), and individual sizes.

The instrument is currently programmed to collect data for 1 minute every 15 minutes. All data are stored in the buoy for post processing. Reduced data in the form of a target-strength graph and integrated intensity for 10 depth intervals at each frequency are averaged over a specified time interval, nominally 2 hours, for daily transmission to shore. Real-time VHF one-way radio telemetry is also available. BIOSPAR has been deployed on three occasions: once tethered to the bottom on Georges Bank and twice released to drift freely for several days in the Gulf of Maine.



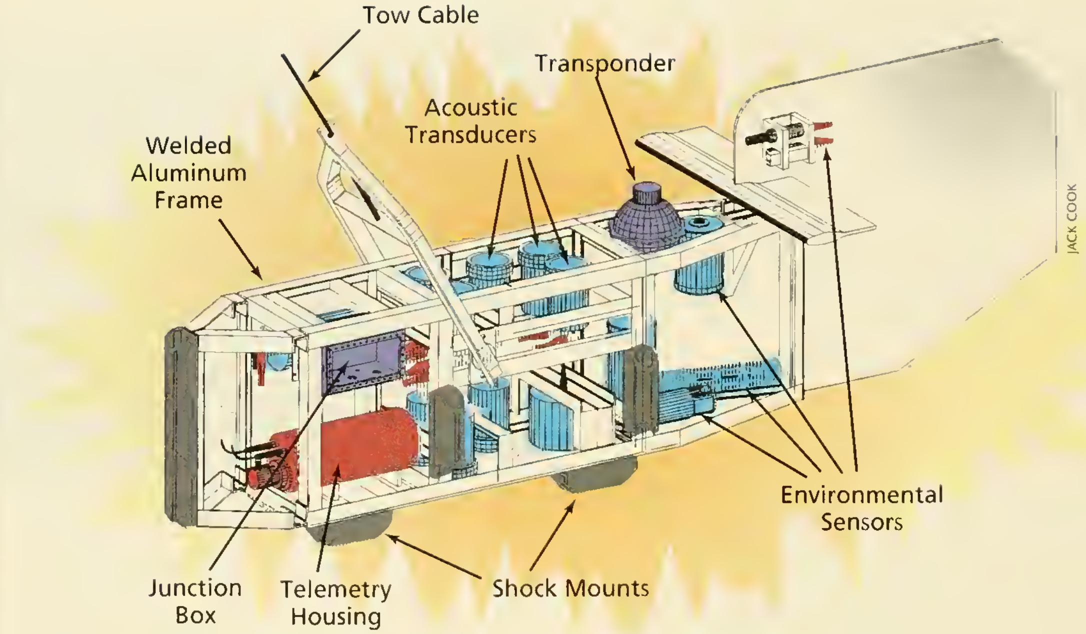
A cross-section of BIOSPAR shows the location and relative size of its components. The instrument is 5 meters tall overall.

BIOMAPER

The towbody assembly is a prototype instrument package dubbed the BIo-Optical Multifrequency Acoustical and Physical Environmental Recorder. A simple aluminum framework accommodates all of the required sensors and allows space for future expansion. Mounting brackets are included for installation of the acoustic sensors in any direction: up-looking, down-looking, or side-looking. Removable, flat, plastic side panels reduce drag and flow noise at high speeds. The framework is 3 meters long, 1.8 meters high, and 0.6 meters wide. It weighs approximately 730 kilograms in air. A tail section adds another 1.5 meters to the length and 0.5 meters to the height.

BIOMAPER's most important instrument is the Bio-Acoustic Sonar System. This system, commercially available from BioSonics, Inc. of Seattle, Washington, is an extremely high-fidelity sonar system designed for absolute measurements of the amplitude of acoustic backscatter received from fish and other marine organisms.

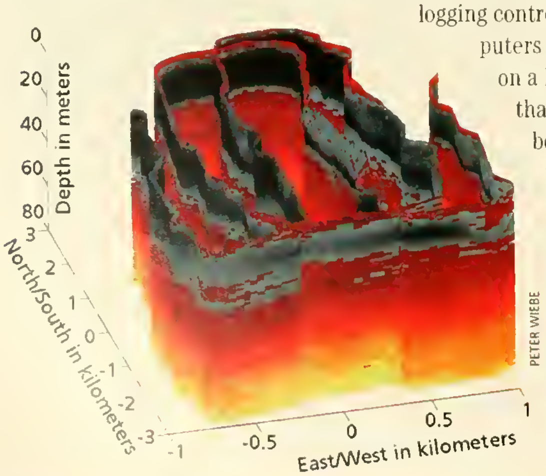
Engineering drawing of BIOMAPER's tow body frame with pressure housings for electronics and transducers and the environmental sensors. When BIOMAPER is in the water, plastic panels cover the framework to reduce drag at high tow speeds (8 to 10 knots).



With system sensitivity high enough to reliably detect and classify echoes from extremely weak targets, such as plankton, in the same depth range as BIOSPAR, it is an important tool for scientists interested in rapidly estimating the distribution of biomass in oceans and estuaries. As noted above, it is essential to measure the backscatter responses of various animals as a function of frequency in order to develop more robust methods of acoustic classification of size and taxonomic type. For this reason the sonar includes multiple transducers, each tuned to a different frequency range. The system is also equipped with an Environmental Sensing System (ESS), that records temperature, conductivity, salinity, pressure, fluorescence (a measure of plant chlorophyll), water transparency, and downwelling light.

The data linkage between the subsea portion and the deck unit allows for communication to the various modules over a common wire pair. The vehicle uses a fiber-optic telemetry system. At the surface, the deck unit is connected directly to multiple computers for display of real-time data as well as logging for post-processing. One terminal acts as the operator's control panel for setting up ping (sound pulse) rates and data-logging controls. The surface computers are connected together on a local area network so that as soon as new data becomes available, scientists can access the files for immediate processing and display.

Three-dimensional BIOMAPER "curtain plot" of the volume backscattering along the trackline of a research vessel in the Wilkinson basin of the Gulf of Maine. The ship's movement along the trackline has been corrected for the drift of BIOSPAR, which was located at the center of the grid.



BIOMAPER, in development for over a year, has been deployed twice. On the first cruise it was used to make multiple rapid surveys around BIOSPAR as the latter instrument drifted in the Gulf of Maine. The purpose was to examine planktonic variability in the space around BIOSPAR so that we could evaluate the data that BIOSPAR was recording.

The second deployment, in February of this year, was intended to map the plankton distributions on Georges Bank. Midway through the cruise, as a vicious gale was bearing down on R/V *Endeavor* (University of Rhode Island) and the ship was pitching badly, the towing wire parted and BIOMAPER was lost in 130 meters of water. (See page 17.) Our recovery attempts, while not yet successful, are ongoing. In spite of this setback, BIOMAPER represents a new means of rapidly surveying substantial ocean areas to determine their status and to set the stage for additional research. The development of these tools is also forcing the development of rapid data processing and real-time visualization techniques. While we cannot yet see a three-dimensional image of animal distribution develop before our eyes as we conduct the surveys, that possibility is not far away.

Development of BIOSPAR was supported by the National Science Foundation (NSF) and the Office of Naval Research. BIOMAPER has been funded by NSF, the National Oceanic and Atmospheric Administration, and WHOI.

Growing up near the seashore in central California, Peter Wiebe developed a love for and a curiosity about the oceans at a very early age. After undergraduate studies in Northern Arizona, a region whose oceans disappeared 40 million years ago or so, making Wiebe a little late to be able to study them, he gained his formal training in biological oceanography at the Scripps Institution of Oceanography. His research interests center on the quantitative population ecology of zooplankton, emphasizing small-scale distribution and abundance, organic matter transport into the deep-sea, the biology of Gulf Stream rings, zooplankton associated with deep-sea hydrothermal vents, and acoustical imaging of zooplankton. He serves as chairman of the US GLOBEC (GLobal Ocean ECosystems) Georges Bank Program.

Neptune's Perversity:

Losing BIOMAPER (Temporarily, We Hope!)

Developing oceanographic instruments can be a tricky, nerve-wracking business, especially when a one-of-kind instrument is lost at sea, as BIOMAPER was just after midnight on February 15, 1995. However, the oceanographic community's response to such disasters speaks to the community's strength and spirit of collaboration.

BIOMAPER was part of a cruise aboard the University of Rhode Island's R/V *Endeavor* to conduct a broad-scale survey of Georges Bank. Working conditions on a frigid February 14 were excellent with low winds, sunny skies, and low sea and swell. As we began a station on the southeast corner of Georges Bank in the early evening, winds were increasing, but seas were still moderate and working conditions reasonable. However, conditions began to deteriorate rapidly, and we cut back on the station's work and began to secure gear.

BIOMAPER is recovered for maintenance aboard R/V Endeavor *(University of Rhode Island) in February 1995. Later in the cruise, the instrument was lost during a similar recovery.*

BIOMAPER had been in the water for most of the last 24 hours and needed to be recovered. I went to the bridge to inform the mate and ask for the bosun's assistance. When the recovery team assembled on deck about 20 minutes later, the ship was beginning to pitch and roll dramatically in the teeth of a fierce, bitterly cold wind. Just before recovery seemed imminent, I went into the main lab to shut down BIOMAPER's data-logging programs, not knowing that the next few minutes would be the most frightening of my many experiences at sea. With deckhands ready to recover the instrument, a pair of large waves completely submerged the stern twice. The first submergence sent us scrambling for hold fasts to avoid getting too wet or being swept away. After the first wave passed, the bosun, facing aft ready to operate the winch, saw the 725-kilogram BIOMAPER emerge completely from the water and then fall back in. The second wave carried less water, but proved fatal for BIOMAPER. The tow cable slackened and dropped nearly to the deck; the towfish was apparently still going down when the stern lifted, snapping the cable taut. The wire caught seaman Dick Foley and lifted him up and nearly over the port rail. The cable parted with a loud crack. Scientific technician Jim Gibson and I retrieved Foley, who was struggling on the far side of the rail—and then registered BIOMAPER's loss.

We had no recovery equipment aboard, so there was nothing to do but continue the cruise with the remaining gear. When we reported the loss to project engineers ashore, their encouraging reply said that a rescue effort could and would be mounted. When we returned home, others within the Institution called to offer assistance. Space and time for a recovery effort were worked into a Global Ocean Ecosystems cruise to service Georges Bank moorings in March from R/V *Seward Johnson* (Harbor Branch Oceanographic Institution). Based on precise positioning and bathymetry data recorded before and after the loss, we concluded that BIOMAPER rested in 125 to 140 meters of water. We drew a 200-by-500 meter "search box" and planned to use a borrowed side-scan sonar and cable and a rented remotely operated vehicle (ROV) to survey the loss site.

After two days of successful mooring work, we started the side-scan work at the BIOMAPER site in light winds and calm seas. The side-scan system was in the water by 0630. Initial returns looked promising: We could discern subtle differences in the flat bottom topography, so it appeared the system would be able to resolve a target the size of the towfish. About 0640 hours, while most of us were in the main lab watching the side-scan record, the bridge corrected course by turning to port. The towing wire went under the stern, and a couple of loud "cachunks" sounded. I ran out onto the deck to see what had happened and found the tow wire hanging limply from the sheave mounted high on the side A-frame. The incredible had happened: In almost the same place where disaster had struck BIOMAPER, the side-scan sonar had suffered a similar fate!

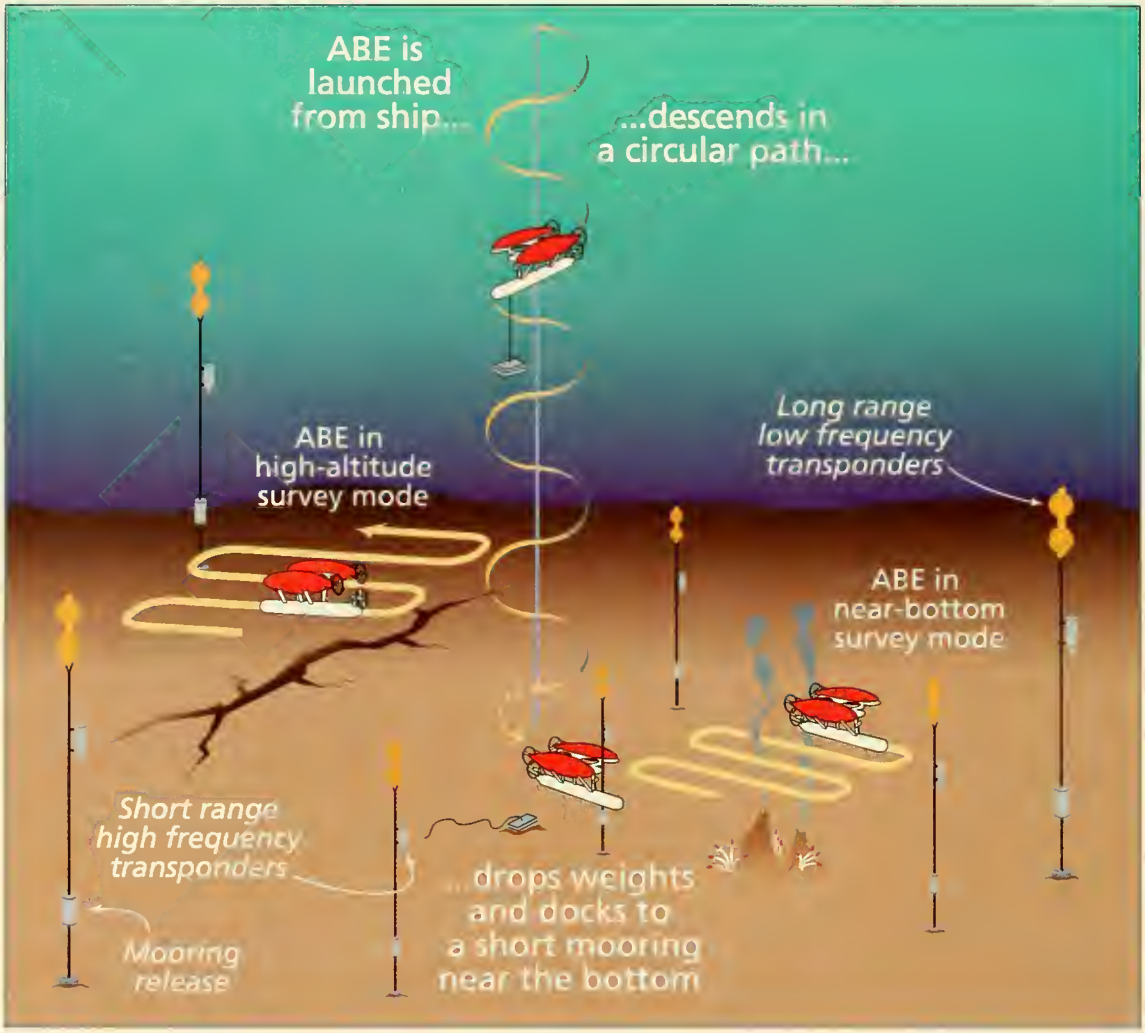
We were devastated, and it took some time before we could think what to do next. Within an hour, however, we had devised a grappling line, and we dragged the area repeatedly during the next 24 hours. With time running out, our luck shifted, the grapnel caught, and we had the sonar system back on deck—still in working order! Though we were able to continue the search for BIOMAPER later that day as well as later in the cruise, and a number of possible sonar targets looked positive, conditions did not allow us to launch the ROV.

The good news is that we have several prospective locations for BIOMAPER, and our Harbor Branch colleagues have kindly planned summer training dives for their *Johnson-Sea-Link* submersible at the BIOMAPER site.

The saga of BIOMAPER's loss is not yet over, but willingness to provide assistance in time of need is clearly a mark of the spirit that pervades the oceanographic community—a spirit that makes this community highly successful in the face of adversity on the high seas. —*Peter Wiebe*

On July 10, just as Oceanus went to press, Wiebe learned that BIOMAPER had been recovered, thanks to the dedication and determination of the R/V Edwin Link's officers and crew.

ABE *will be launched by a surface ship and glide to the work area. Once near the bottom, its first job will be to find its hitching post and make sure it has a safe place to rest. Once docked,* ABE *will not have to worry about currents carrying it away from the worksite while it is asleep in its low power mode.* ABE *will then be programmed to periodically wake up, undock, and travel to a series of prespecified locations around the area of interest to snap single frame video images or make other measurements. After finishing its preprogrammed survey,* ABE *will return to its docking point, reattach itself, and shut down until the next scheduled event.*



JACK COOK

An AB(L)E Bodied Vehicle

Albert M. Bradley
Senior Engineer, Applied Ocean Physics & Engineering Department

Dana R. Yoerger
Associate Scientist, Applied Ocean Physics & Engineering Department

Barrie B. Walden
Principal Engineer, AOP&E, and Manager, Submersible Engineering & Operations

The Autonomous Benthic Explorer, known to its friends as *ABE*, is a robotic vehicle designed for deep-ocean exploration and monitoring. *ABE* is an example of the class of systems known as Autonomous Underwater Vehicles, or AUVs, that are being developed for a variety of missions by military and civilian groups. *ABE* is different from most of the other AUVs under development in that it is designed for long-term monitoring missions and will spend the majority of its time asleep, attached to a simple hitching post near the area of interest. At regular intervals *ABE* will wake up, let go of the latch, and, using an acoustic navigation system to guide its movements, travel around its survey area taking video snapshots and making a variety of measurements. At the end of the survey, *ABE* will return to its hitching post, latch on, and, like a mountain climber roped into a hammock on the face of a cliff, simply go to sleep until the next scheduled survey.

The Mission

ABE is designed for a wide variety of missions, but foremost is monitoring geological and biological changes in hydrothermal vent regions. These dynamic structures occur in seafloor-spreading areas along the mid-ocean ridges where the proximity of the underlying magma drives an associated hydrothermal circulation. (See *Oceanus* back issues including Summer 1979, Winter 1988/89, and Winter 1991/92 for descriptions

and discussions of this phenomenon.) While hydrothermal vents are better understood than they were a decade ago, further observations are required to answer many basic questions. For example, the chemical flux from the vents may dominate and stabilize the global, long-term composition of seawater, or it may be trivial, depending on whether the high or low value of the best available estimates of total flux is used. We know very little about the temporal variability of the vents: Magma may be delivered to the surface steadily or in batches. It appears that there are both steady emissions and periodic releases of large amounts of water (called megaplumes) that may play a role in the ocean's heat balance.

Ship time is expensive, and a research ship can only remain in one area for a limited time. As a result, months or years usually pass between visits to a particular site. Often, when scientists return to an area of active venting, many of the features have changed dramatically. We have only limited knowledge of how these complex systems evolve. *ABE* can remain on station near an area of interest for many months, waking up daily to travel around the area and record the evolution of the biology and geology. The data gathered might include several time-lapse movies showing the growth of a sulfide chimney or a clump of tube worms, as well as a host of oceanographic variables.

The figure opposite shows a typical *ABE* mission. For the first time around, we'll be waiting on the ship above, listening intently to acoustic signals from ABE as it reports on its progress. If all goes well, the ship will then leave the site and ABE will repeat the surveys entirely on its own. Eventually, when its batteries are depleted, it will simply wait at its dock for the ship to return and send an acoustic command for it to return to the surface. *ABE* can remain quiescent at its dock for several months, and its periodic excursions can be spread out over that entire time.

Why Such a Strange Shape?

ABE's configuration is unlike most other AUVs. Most are torpedo shaped and designed for speed and range; they are optimized to survey oceanographic variables of interest (such as salinity and temperature) over wide areas. Some of these vehicles will eventually be able to travel several thousand miles. For *ABE*, the ability to maneuver in tight places close to complex bottom topography is more important. *ABE*'s three-body shape gives it several unique advantages. First, it allows reasonably efficient forward travel, yet provides protected locations for the lateral and vertical thrusters. Second, with all the buoyancy in the upper pods and the weight concentrated in the central lower body, *ABE* has excellent stability. Torpedo-shaped vehicles tend to roll and pitch easily and must either maintain forward motion or expend thruster energy to remain level. *ABE* is very stable, which makes automatic control a lot easier and makes it a better sensor platform, particularly for sonar systems.

ABE also moves slowly compared to other vehicles.

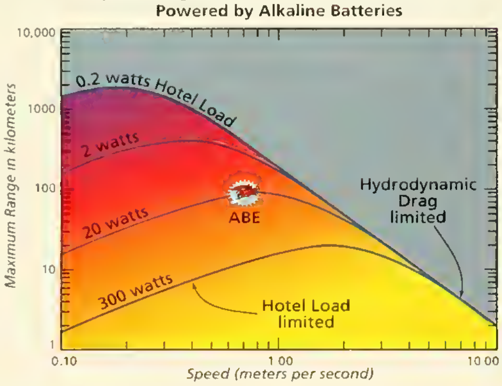

AL BRADLEY

ABE *hovers just below the surface in tests off the WHOI pier.*

For travel through the water on a limited energy budget, the slower you go, the further you can travel. This regime is definitely a situation where slow and steady wins the race! The reason is that hydrodynamic drag increases as the square of the speed through the water. If you go twice as fast, the drag (and hence the thruster force required) increases by a factor of four. If you go fast, you'll arrive at your end point sooner, but you'll have to work a lot harder to get there. In practice, there's a limit to how slow you should go. *ABE* must always be able to move faster then the currents it encounters around its work area or it could be swept away from its home base and have to expend a lot of energy driving up-current to return. The currents around the hot vent areas we hope to study are typically a few centimeters per second, so if *ABE* travels about 50 centimeters per second (about 1 mile per hour), it should be able to get the job done.

Another lower limit on how fast to travel results from what is known as the "hotel load" of the vehicle. This term, which comes from ship design, refers to the energy needed by the vehicle in addition to that used for propulsion. For example, on a cruise ship, the power used for lighting, air conditioning, and running the stoves in the galley all contribute to this value, hence the term hotel load. *ABE* doesn't have any of these amenities, but it still needs power for navigation and for running its sensors and control system. "Metabolism load" might be a better term for *ABE* than "hotel load." One of the biggest power hogs is the xenon flash used to illuminate the scene whenever a video snapshot is required. We've worked hard to keep the metabolism down, and *ABE* can think and navigate on about 20 watts. To see how this determines the best traveling speed, imagine going very slowly and only

Speed-Range Trade-Off for an ABE-Sized AUV Powered by Alkaline Batteries



JACK COOK

The 20 watts of power ABE *needs to "think and navigate" (its "hotel load") affects the vehicle's speed and range.*

devoting a few watts to propulsion. It will take forever to get anywhere, and in that time the metabolism load will use up all the energy available. Of course, if you go too fast, you'll get there sooner, but you'll leave a lot of energy behind in the form of swirling water (too much hydrodynamic drag.)

The bottom line is that there's an optimum speed that will get you as far as possible by partitioning the available energy wisely between travel and metabolism. Figure 2 shows this relationship for *ABE*.

We've measured *ABE*'s energy use carefully and, with the present lead-acid battery pack, the vehicle can travel a total of 17 kilometers at 70 centimeters per second. We are using these batteries during the development phase of *ABE*'s life since they are easily recharged. Eventually they will be replaced by packs of alkaline D-cells (regular flashlight batteries), which will nearly quadruple ABE's range. If we replace the alkaline batteries with lithium cells, *ABE* can travel 12 times farther (over 200 kilometers) than it can with the lead-acid batteries.

ABE *is recovered after a dive in the Pacific. Swimmers assist vehicle recovery by attaching the lift lines.*

AL BRADLEY

ABE's First Jobs

ABE, developed over the last four years, has been through a series of tests in local waters and in the deep ocean, but its first real science mission is planned for September 1995. This will be a survey of the magnetic field of a 1993 lava flow on the Juan de Fuca Ridge about 200 miles west of Seattle at a depth of over 2,000, meters. This survey, under the direction of WHOI geologist Maurice Tivey and cruise chief scientist Paul Johnson (University of Washington), will be carried out in conjunction with more traditional survey work using the three-person submersible *Alvin*. For this mission, *ABE* will not attempt to dock but will spend all its battery power patiently zigzagging back and forth across the area of interest recording magnetic field variations to determine the areal extent and thickness of the new, highly magnetic lava flow and its relatively nonmagnetic subsurface dike or feeder channel. We will launch *ABE* in the evening after *Alvin* has completed its daily dive, and recover *ABE* before *Alvin's* next launch the following morning.

For its next mission, we plan to launch *ABE* at the beginning of an *Alvin* dive series, and allow it to run autonomously for a period of about 10 days. During this time, *ABE* will undock from its hitching post each day, conduct a survey, then return to its dock.

After gaining confidence through these tests, we will finally leave *ABE* on its own for a period of several months. We hope at that time to include *ABE* in a planned underwater Acoustic Local Area Network (ALAN) in interesting vent areas. ALAN will operate like a slow Internet, allowing us to communicate from our labs with oceanographic instruments deployed around a vent site. This exciting new technology will allow us to get periodic updates and alter *ABE*'s programming from shore. We will be able to get brief glimpses of the data *ABE* is collecting and redirect its mission to take better advantage of changing conditions.

ABE*'s development has been funded by The National Science Foundation.*

Al Bradley was educated by his parents and a long series of exasperated teachers including those at Cornell (where he received BS and MS degrees in engineering physics in 1966 and 1967) and at MIT where he received his PhD in Ocean Engineering in 1973. After a brief postdoctoral position at MIT, he came to the Woods Hole Oceanographic Institution where he is classified as a Senior Engineer (but would prefer the title of Toymaker).

Barrie Walden joined the *Alvin* Group in 1969 as a freshly-graduated Florida Atlantic University ocean engineer. As the group's newest member, he was assigned responsibility for the final stages of habitability improvement of the submersible's support ship R/V *Lulu* and says he has been working his way up from that failure ever since. (*Lulu* was a nortoriously less-than-comfortable ship, despite anyone's efforts!) He became involved in scientific saturation diving programs, and eventually spent two and a half years managing Fairleigh Dickinson University's Hydrolab Project on St. Croix, USVI. He returned to Woods Hole with a lot of island life experiences and a good tan, and became manager of the *Alvin* Group just in time to take some of the credit for conversion of *Atlantis II* to a submersible support ship. Walden also manages WHOI scientific marine operations.

Dana Yoerger's research interests are based in improving the sampling and survey capabilities of underwater vehicles using improved automation and robotics. He has built robotic control systems for a variety of remotely operated and autonomous vehicles, including *ABE* and the remotely operated *Jason*. Yoerger, who hold SB, SM, and PhD degrees in mechanical engineering from MIT, says people often ask him when he's going to get a real job!

ELLYN MONTGOMERY

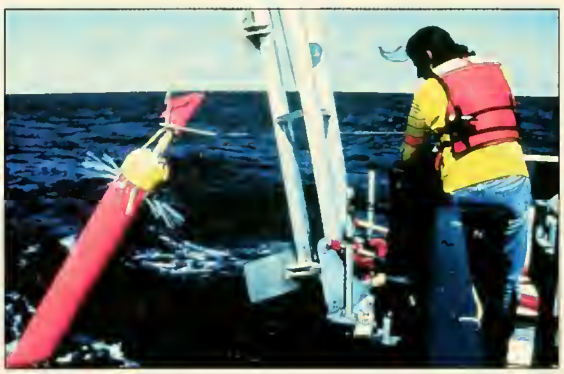
The high resolution profiler is ready for action on the deck of R/V Oceanus.

A Free Vehicle Explores Deep-Sea Mixing

Raymond W. Schmitt,
Senior Scientist, Physical Oceanography Department
Ellyn T. Montgomery
Information Systems Associate II, Physical Oceanography Department
John M. Toole
Associate Scientist, Physical Oceanography Department

Imagine attaching weights to half a million dollars worth of sophisticated electronics, dropping it into a patch of 3.5-mile-deep open ocean, and expecting it to go to the bottom and return in a few hours. It takes a lot of faith in "silicon brains" to attempt such a feat! Having done it once, one might hesitate to risk it again. However, that is what we do with our High Resolution Profiler (HRP) on a routine basis. Indeed, the HRP has made over 450 such dives on five separate cruises in two different oceans and a wide variety of sea conditions.

We are interested in ocean mixing processes. Mixing is an important part of the general circulation of the ocean, as it provides the warming that allows cold, deep water, formed by cooling near the poles, to rise again to the surface. This mixing is thought to be caused by turbulence resulting from the "breaking" of subsurface internal waves or from flows over rough topography. To measure the turbulence, sensitive and precise instruments must be deployed from stable, vibration-free platforms. Because mixing in the cold bottom waters is of special interest, it is important to be able to make measurements near the seafloor.

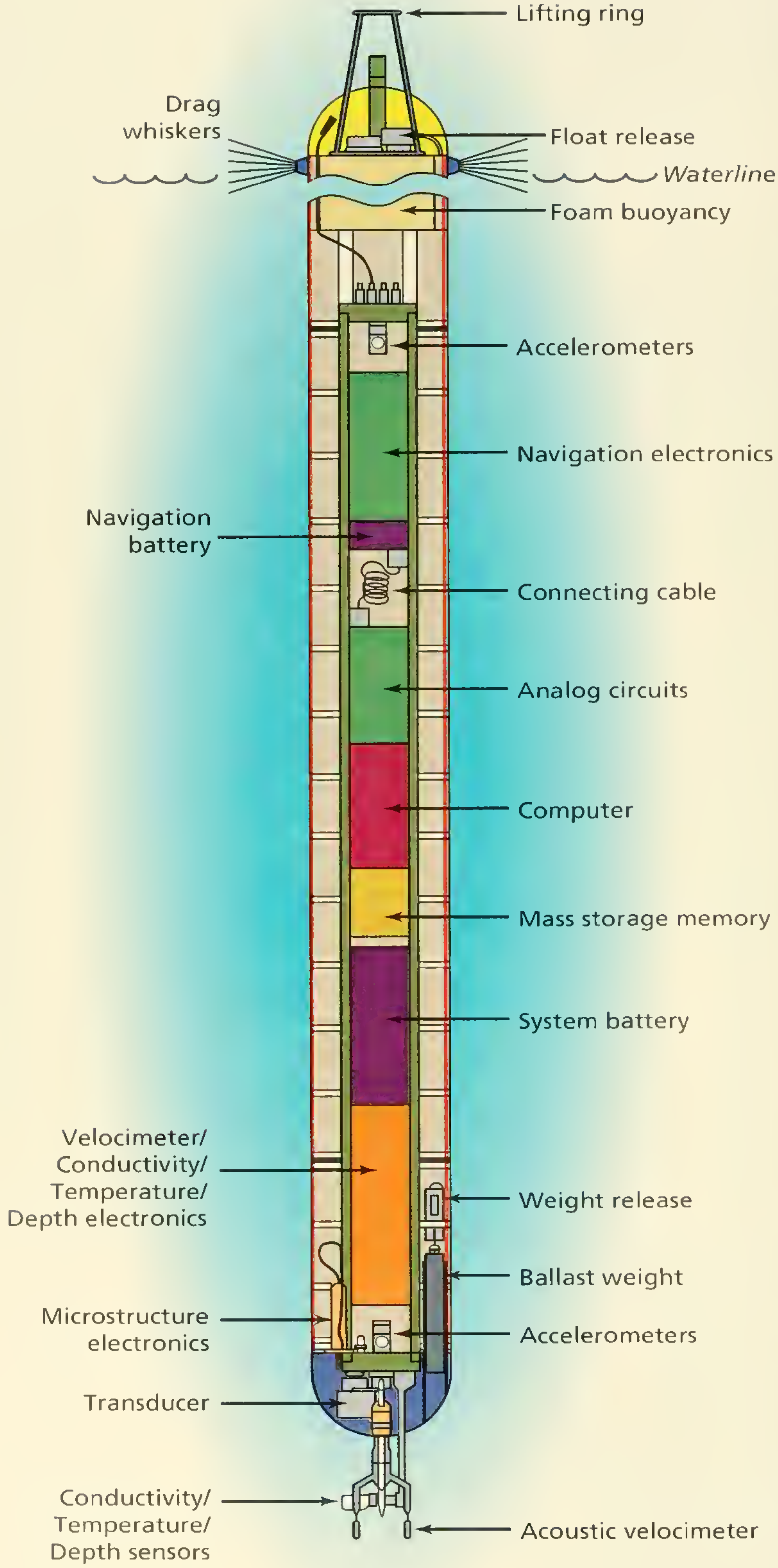


ELLYN MONTGOMERY

MIT/WHOI Joint Program graduate Kurt Polzin deploys the high resolution profiler.

Most ocean soundings are accomplished using instruments secured to the ends of wires that roll from shipboard winches. However, the vibration and irregular fall rates of wire-lowered instruments preclude their use for ocean-mixing measurements. Thus, we took the riskier road of designing a free-fall device.

Free profilers have been in use for over 20 years in oceanography. Until the development of newer instruments like the HRP, working with free vehicles posed a number of difficulties.



Cross sectional view of the high resolution profiler showing electronic components. The total length of the profiler is 5 meters including the additional buoyancy not shown.

There were three areas of potential trouble:

- instrument tracking and location,
- over-the-side handling during deployment and recovery, and
- power and data storage and transfer requirements.

In the 1970s, open-ocean use of free profilers depended on early satellite navigation systems, with many hours between fixes, so that knowing the ship's position from deployment to recovery was one of the biggest obstacles to success. The balky, hand-held radio direction finders used to locate an instrument after it had resurfaced brought constant frustration, because their signals reflected off the ship's metal superstructure. Acoustic tracking on the ship's precision depth recorder was a black art, highly dependent on sea state, thermocline structure, and distance from the instrument. (The thermocline is a region of rapidly descending temperature that strongly distorts the paths of acoustic signals.) Data were recorded on limited-capacity magnetic tapes, so researchers had to open the instrument's pressure case between dives to change the tape. Batteries also had to be replaced or recharged frequently, adding to the number of pressure-case openings. Each opening entailed breaking one or more O-ring pressure seals and remaking the seal for the next dive, and there was always a risk that a stray hair or bit of dirt across an O-ring could cause a leak sufficient to sink the instrument. For instruments too large to take into the ship's laboratory, tapes and batteries had to be exchanged on the open deck of the ship—hardly the ideal spot to assure a clean, dry atmosphere for the electronics.

Another problem with large instruments was the need to protect the fragile sensors at the lower end. Often, a small rubber boat would be launched to assist with each recovery and avoid contact between ship and instrument. The occupants of the rubber boat would attach the hook of the ship's crane to the profiler so it could be lifted from the water well clear of the ship. This routine restricted deployments to "fair-weather" situations, and added a great deal of time to the dive cycle. Even when every mechanical and electrical system worked well, the slow, often troublesome tape players combined with the limited computing power available in those days allowed only cursory perusal of data at sea. Often, all the researchers knew was that the tape had advanced—they could discover months later that the sensors were not functioning properly. A three-week cruise might accomplish only 10 or 20 dives, a data rate inadequate to address many physical oceanography research questions.

By the early 1980s, our experience with such vehicles and rapidly evolving technology led us to the conclusion that many free-profiler problems could be resolved with a systematic redesign of major elements and the use of new, low-power microprocessors. We set out to build an instrument that could be used in nearly any weather, day or night, with the capability to quickly offload and review data. We submitted proposals to the Department of Defense and Office of Naval Research for

a two-year development effort. These were successful, and an intense period of design and construction ensued in 1983.

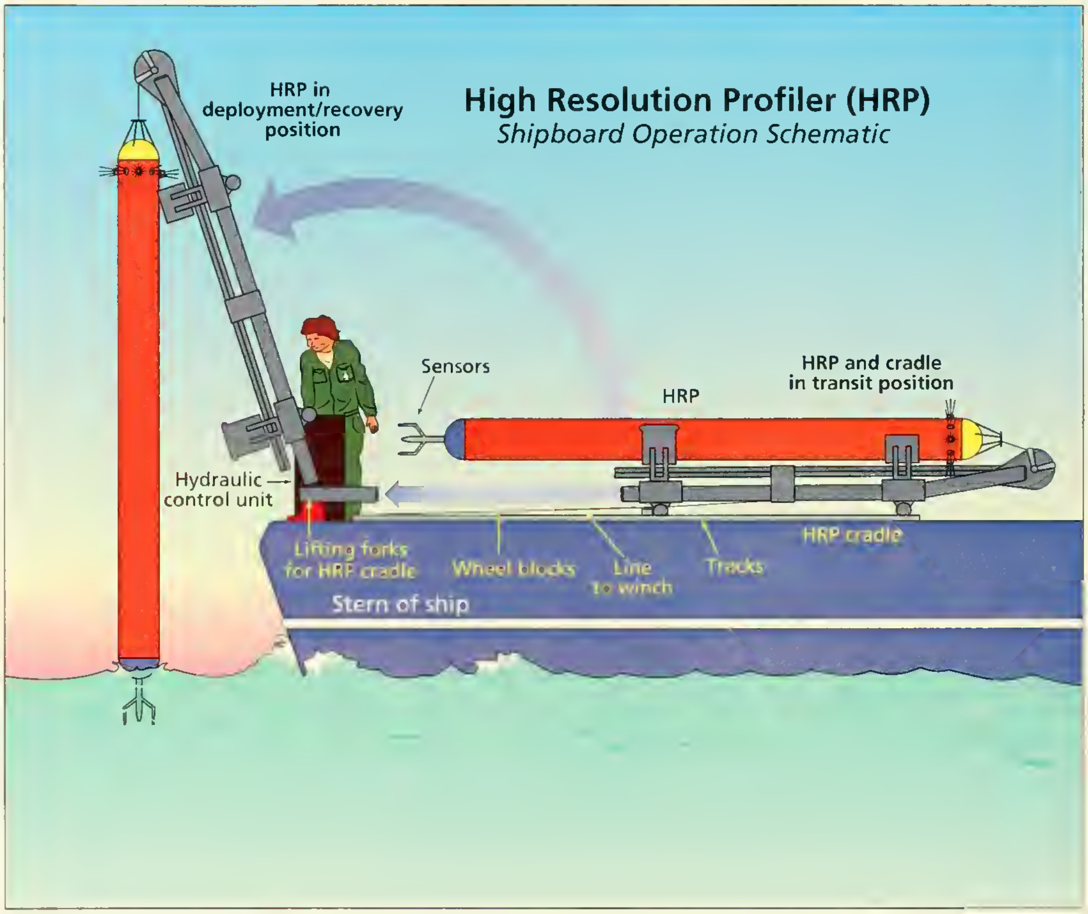
We began by specifying the measurements the instrument would make: temperature, salinity, pressure, and horizontal velocity. These "fine-scale" variables would be recorded at 10 times per second, as they did not need to be very closely spaced. At the 60-centimeter-per-second fall rate planned, they would be 6 centimeters apart, quite sufficient to calculate the derived variables we needed on 1-meter scales. To interpret the data from the velocity sensors we also needed information on the instrument's orientation and tendency to wobble, so we included an internal compass and fine-scale accelerometers. Another set of variables would have to be recorded 20 times faster, at 200 times per second. These "microstructure" variables of temperature, conductivity, and horizontal velocity, sampled every 3 millimeters in the vertical, would provide information about the intensity of mixing within the water column.

Our interest in reaching the abyssal ocean specified the thickness of the pressure case, and the space occupied by the sensor electronics and computer determined its length and diameter. The weight of these components dictated the ballast needed to sink the instrument and the amount of pressure-resistant, buoyant foam required to bring it back to the surface. As the instrument had by then grown rather large, we decided to use its length to advantage. We placed all the fragile sensors at the bottom of the 5-meter-long instrument so they would be well removed from contact with the ship's hull when the profiler floated upright at the surface with only about half a meter showing above water.

We then had to decide how to handle such a large package. If we relied on the ship's crane to lift it in and out of the water, the uncontrollable pendulum motion induced by the ship's roll would make it all too easy to smash the sensors against the rail of the ship. Our engineering team met this challenge with a special winch and tilting rig that included a cart for storing the profiler in a horizontal position on deck.

With the cart tilted up to deploy or retrieve the instrument, the lower end of the instrument would be in the water, minimizing swinging even in rough seas. As the forks tilted back, the profiler would settle neatly into its cradle. Back on deck, the profiler could be wheeled forward away from the stern for easy access to its "business end." The main body of the HRP was designed with a flexible "exoskeleton" and a tough plastic skin to cushion the metal pressure case and electronics against contact with the ship's hull.

To minimize pressure-case openings, we wanted a high-capacity battery that would allow many deployments between battery changes. A large pack of alkaline batteries proved to be simple and economical. Battery specification was made easier because computers and sensors available in the early 1980s consumed much less power than their predecessors. Also, we could now use solid-state memory to record the data rather than magnetic tape. Thus servicing the instrument between dives required only a transfer of data and the attachment of new weights. More recently, the use of modern minicomputers in the shipboard laboratory has opened new possibilities. They now make it feasible to perform detailed analyses of the large data sets shortly after a dive, so that sensor performance can be monitored in detail. Equally important, we can quickly examine the data of oceanographic interest and modify our sampling strategy to best suit the observed phenomena. For example, if mixing is particularly strong in one area, we can focus our attention there.



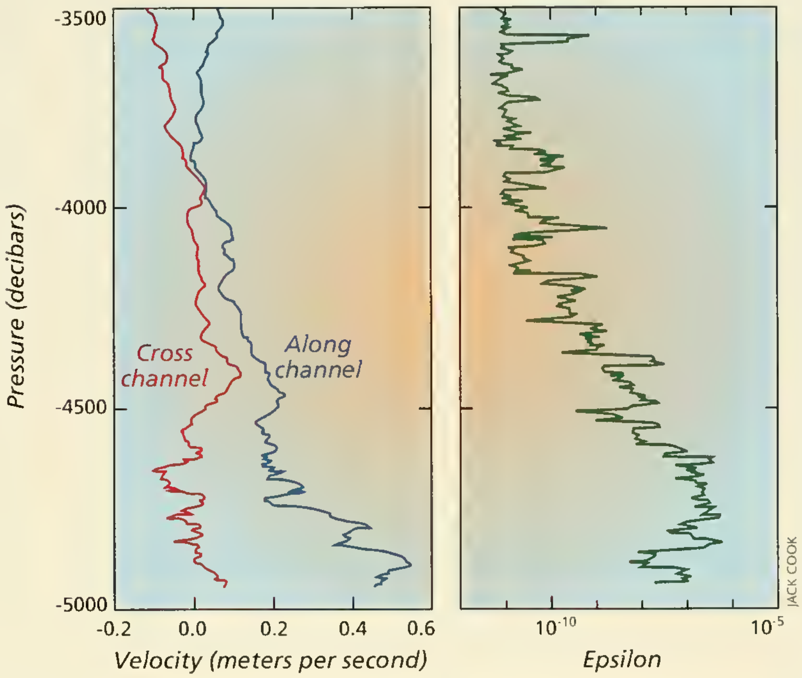
JACK COOK

A special winch and tilting rig minimizes the risk of damaging the high resolution profiler on launch and recovery and allows operation in rough weather.

Other advances have come in the area of tracking and navigation. More powerful radio beacons, with improved direction finders mounted high on the superstructure of the ship, have made locating the profiler after a dive a fairly routine event—though the warble of the radio beacon as the profiler breaks the surface is still cause for celebration. By placing an acoustic beacon at the bottom of the profiler we can monitor its range from the ship, even as it drifts on the surface. Because we now have precise navigation in the satellite-based Global Positioning System (GPS), we can return to the deployment position when the profiler is due at the surface. In most of the open ocean, the net currents are not very large, so the HRP tends to surface within a few hundred meters of where it was launched. GPS lets us know exactly where to go. At night, a flashing strobe light and a chemically luminescent "glowstick" help us home in on the instrument. A successful daytime recovery is shown in the photo opposite.

But all of these location aids would be for naught if the instrument failed to drop its weights at the bottom of a dive. We have built in numerous safeguards to assure its return from every dive. We rely on electronic logic, physics, chemistry, and acoustics to provide means of dropping the weights. The most frequently used method is the measured ambient pressure; when that exceeds the threshold specified for the dive, solenoids are triggered to release the weights. We also rely on elapsed time, using two different timers. If for some reason the HRP failed to reach the expected pressure within a given time (perhaps because of misballasting or landing on an uncharted seamount), the computer timer, or a simple backup timer if the computer had failed, would send the release command. When we wish to approach the bottom, we employ a small echo sounder and use the measured distance above the seafloor as the primary logic for dropping the weights. In addition, these electronic devices are backed up by simpler mechanical and chemical means.

A wire-restrained piston is part of the release mechanism. When the pressure exceeds the strength of the wire (which depends on the chosen thickness) the weight is dropped. Finally, a small piece of magnesium wire holding each weight corrodes within a few hours in seawater, providing one last method for dropping the weight. We use two weights to sink the profiler; dropping either one will cause it to return. We have exercised every one of these release techniques, either intentionally or by necessity, in the course of more than 450 dives, and are glad to have all of them. Our first dives were made in the spring of 1986, and, to our delight, the HRP proved to be a robust, well-behaved instrument from the start.



High resolution profiler data taken in the eastern part of the Romanche Fracture Zone shows enhanced velocity and mixing in the along-channel direction. The left portion of the figure shows the velocities rotated from east and north to cross- and along-channel components. The right portion shows epsilon, a measure of the intensity of turbulent mixing.

While there is great risk in deploying such sophisticated instrumentation in an unforgiving ocean, the payoff makes it worthwhile. With our complete suite of fine-structure and microstructure variables, we have shown that certain relationships hold between the energy of the internal wave field and the intensity of small-scale turbulence. This promises to lead to a useful parameterization of mixing due to internal waves. With our ability to work in moderately rough seas, we have been able to work in an eddy spun off the Gulf Stream in the wintertime North Atlantic, even through snowstorms. There we discovered that the flow field of such eddies harbors especially intense internal waves and enhanced mixing. Working near the bottom, we have discovered intense mixing above and around an open-ocean seamount that is associated with tidal-flow oscillations. In a large open-ocean area of the eastern Atlantic we have made a systematic survey of mixing in the water column, correctly predicting the observed dispersion of a tracer before it was injected in 1992 by Jim Ledwell and colleagues about 800 kilometers west of the Canary Islands. And on our last cruise in November-December 1994, we made the first measurements of turbulence levels in the abyssal ocean.

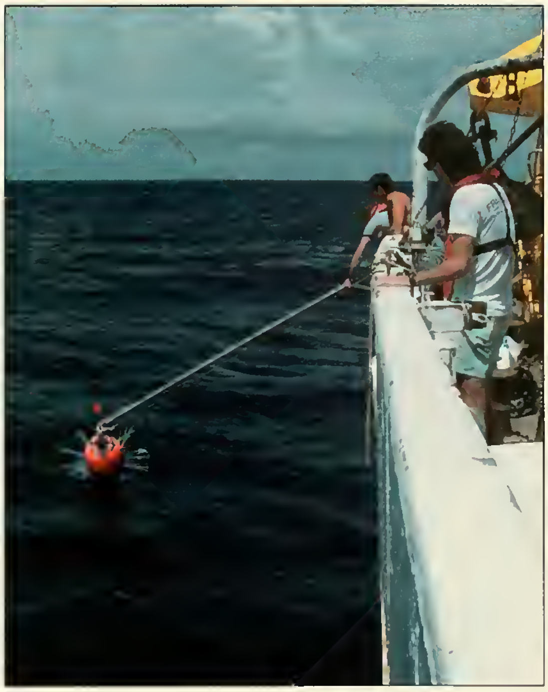
The site of this recent work was near the equator in the central Atlantic, at the Mid-Atlantic Ridge, the underwater mountain range bisecting the deep ocean basin into eastern and western portions. In most places the ridge is high enough to prevent the coldest bottom water found in the western basin from penetrating to the east. However, near the equator, two narrow chasms known as the Romanche and Chain fracture zones cut across the ridge. They provide narrow can-

yons where deep water can flow from the western to the eastern basin. We worked from the French research vessel *Noroit* with French scientists who had deployed an array of current meters in the fracture zone. The HRP is uniquely suited for this work since it is the only turbulence profiler capable of going to such depths (5,500 meters) and can use its acoustic altimeter to prevent a collision with the steep topography of the fracture-zone area.

On this cruise, our first dives to such depths revealed some problems in turbulence-probe performance. Some of them were leaking under the intense pressure encountered (more than 8,000 pounds per square inch). But we quickly selected those probes that could survive the trip and began a systematic study of velocity structure and mixing within the abyssal canyon.

The results were quite exciting. While other parts of the deep ocean have proven to be quiet and only weakly turbulent, the near-bottom flows in the canyon were anything but calm: We found strong, bottom-intensified, very turbulent flow (see figure opposite). Indeed, it was as turbulent as the ocean surface layer on a windy day. As the cold water flows over the sills and bumps in the bottom of the fracture zone, it mixes strongly with the warmer water above. Evidence for this mixing could be seen in the change in bottom temperatures along the axis of the canyon. A good analogy for what we observed is the flow of a river through a stretch of rapids. However, this salt-water "river" has 10 times the flow of the Amazon (the largest of all rivers) and the rapids are more than 5,000 meters below the sea surface!

On its 450 dives, the High Resolution Profiler has sampled more than 780 vertical kilometers of ocean with a resolution of a few millimeters. This remarkable track record is due to systematic advances in all phases of ocean engineering and technology, particularly in the application of new microelectronic circuitry. But it also owes much to the quality engineering put into its construction by members of the Advanced Engineering Lab based in the Applied Ocean Physics and Engineering Department, including Dick Koehler, Ken Doherty, Dale Fairhurst, and Ed Mellinger, and to its ongoing maintenance by David Wellwood of the Physical Oceanography Department. Though it is approaching its 10th birthday, we fully expect the profiler to contribute to further exploration of mixing in the deep sea. Our next project will be another comparison with a tracer release experiment, this time in the deep waters of the Brazil Basin of the South Atlantic. The question of where and how the deep water is warmed by mixing is one of the outstanding problems in physical oceanography, and the HRP is uniquely able to address it.



TOM BOLMER

Special lightweight latching hooks invented by Sandy Williams are used to snag the high resolution profiler alongside the vessel. In rough seas (12-foot waves and 25 knot winds), retrieving the profiler can be quite an adventure—similar to landing a 900-pound tuna!

Construction of the High Resolution Profiler was supported by Department of Defense and Office of Naval Research (ONR) funding. Research operating funds have come from ONR and the National Science Foundation. The profiler is described in "The Development of a Fine- and Microstructure Profiler" by R. W. Schmitt, J. M. Toole, R. L. Koehler, E. C. Mellinger, and K. W. Doherty in the Journal of Atmospheric and Oceanic Technology, *Vol. 5, No. 4, 1988, pages 484–500. Some recent results are given in "Estimates of Diapycnal Mixing in the Abyssal Ocean" by J. M. Toole, K. L. Polzin, and R. W. Schmitt in* Science, *Vol. 264, 1994, pages 1120–1123, and in "Finescale Parameterizations of Turbulent Dissipation" by K. L. Polzin, J. M. Toole, and R. W. Schmitt in the* Journal of Physical Oceanography, *Vol. 25, No. 5, 1995, pages 306–328.*

Ray Schmitt has a long-standing interest in the smallest scales of variability in the ocean. He enjoys the overall process of developing and using novel tools for ocean exploration, as they are the primary means by which new knowledge is generated. However, his wife suspects that his seagoing activities are merely an excuse to occasionally escape the challenges of raising a ten-year-old and twin seven-year-old sons, who have elevated sibling rivalry to an art form.

During the last decade, Ellyn Montgomery has used her computer programming expertise to aid a variety of WHOI projects. She enjoys performing "brain surgery" on the HRP as needs for the software change with the focus of research. Along with programming the profiler to operate successfully, she is pursuing the use of scientific visualization tools to better understand and display the data collected.

Attraction to the sea and hands-on ocean science began for John Toole with a keen interest in sailing. He maintains an eclectic research program built around use of new instrumentation to better learn how the ocean works. With WHOI colleagues and his wife (and chief foredeck crew), he also continues to campaign sailing race courses through the summer as research cruise schedules permit.


KEN BRINK

The R/V Thomas Thompson *first mate (left), Jerry Dean, and Julie Pallant recover Seasoar aboard the University of Washington ship following a 1994 "flight."*

Seasoar – A Flying CTD

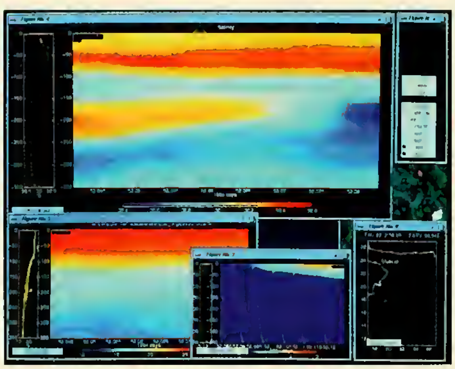
Frank Bahr
Research Associate, Physical Oceanography Department
Paul D. Fucile
Engineer II (Electrical), Physical Oceanography Department

Many of the oceanographic tools described in this issue of *Oceanus* have been devel oped by WHOI scientists and engineers. This process may begin with observation of a need for a particular sort of measurement, then become a back-of-the-envelope sketch, move on to the tinkering stage, and eventually, often over many years' time, blossom into a hardworking oceanographic instrument.

Seasoar took a different route. It is an off-the-shelf tool that WHOI staff have modified to fit their needs. Seasoar is an upper-ocean version of the workhorse CTD (Conductivity, Temperature, Depth) profiler that is ubiquitous in hydrographic data acquisition. (See *Oceanus*, Spring 1991, for the story of the CTD's development.) The CTD requires a research vessel to stop and remain on station while the sensor is lowered over the side to make a variety of measurements and collect water samples in accompanying bottles as it travels down the ship's wire and up again. Including the time to stop and start the vessel, a typical station in 350 meters of water takes about 40 minutes.

Seasoar offers a time- and cost-effective alternative for research projects designed to map the three-dimensional structure of oceanic variables on scales as small as a few kilometers in the upper ocean. It is an undulating airplanelike vehicle that is towed behind a ship at speeds typically around 8 knots. The system in its current form was developed at the Institute of Oceanographic Sciences (Deacon Laboratory) in the UK, and is marketed by Chelsea Instruments Ltd., London. An earlier version called the Batfish was designed in Canada.

Seasoar's vertical range extends from the surface down to about 350 meters. A dive cycle takes about 10 minutes to complete, providing a complete upper-ocean profile approximately every 1.2 kilometers.


TOM KLEINDINST

UNIX display of real-time color contour map that shows Seasoar measurements of salinity (top large screen), temperature (lower left), photosynethically available radiation (lower center–data taken at dawn), and location (lower right).

The vehicle is towed on a 500-meter-long, seven-conductor cable fitted with winglike plastic fairing to reduce cable drag. A special, large-drum winch fits all of the cable on one wrap to prevent fairing tangles. The maximum depth can be increased by adding faired cable, but this usually increases profiling time and thus reduces horizontal resolution.

Seasoar's wings rotate into a

diving or climbing position on command from the surface. Power to drive the wings is derived from an impeller connected to a hydraulic pump. The surface command, an electrical current, positions a valve to extend or retract a hydraulic ram that is coupled to the wings.

We "fly" Seasoar with a PC-based controller that was developed at WHOI. It generates a digital ramp representing an optimal upward and downward flight path that we call "Command." The flight parameters are minimum depth, maximum depth, period of the cycle, and the amount of time Seasoar travels in an upward direction. A pressure sensor in Seasoar reports depth back to the surface. The computer calculates the difference between where Seasoar is and where it is supposed to be. This "error" signal is converted to valve current and sent down the tow cable to adjust the wings and bring Seasoar to the desired depth. Rather than generating this current directly by a plug-in, analog-to-digital board, the PC program sends a digital signal out the printer port into an external current driver that we designed. This gives us the option to fly Seasoar from a laptop computer whose single serial port is needed to import pressure information.

The weight and drag of the tow cable and the vehicle's hydrodynamic properties cause a lag in response time. The computer program accounts for this and makes the wing adjustments at appropriate variable rates. The result is an easily controlled flight with a nearly symmetrical up-and-down profile. Seasoar can also be controlled manually from the computer keyboard.

The original Chelsea Instruments version of the controller was an analog computer that derived its control signals from a specific hardware solution. An oscillator generated the up-and-down ramp (the analog version of "Command"), and a circuit compared the voltage coming up the wire from the pressure sensor to this signal. Again, the difference was sent down the cable as valve current. Front-panel controls tailored the computer's hard-wired feedback loop equation. We learned empirically which parameters would give us good control. The new digital system put less emphasis on the hardware, allowing us to easily reprogram the control equation. This will be especially useful as different sensors are attached to Seasoar, and change its performance.

Originally, basic vehicle-performance parameters such as wing angle and vehicle attitude were not measured. This proved particularly bothersome when the performance of the vehicle deteriorated. To learn more about Seasoar's behavior, Jerry Dean developed an engineering unit to measure vehicle pitch, roll, wing angle, impeller turns, and pressure. The engineering unit has a microprocessor to measure these parameters and send the data up the tow cable for recording and monitoring along with cable tension, the Command signal, and valve current.

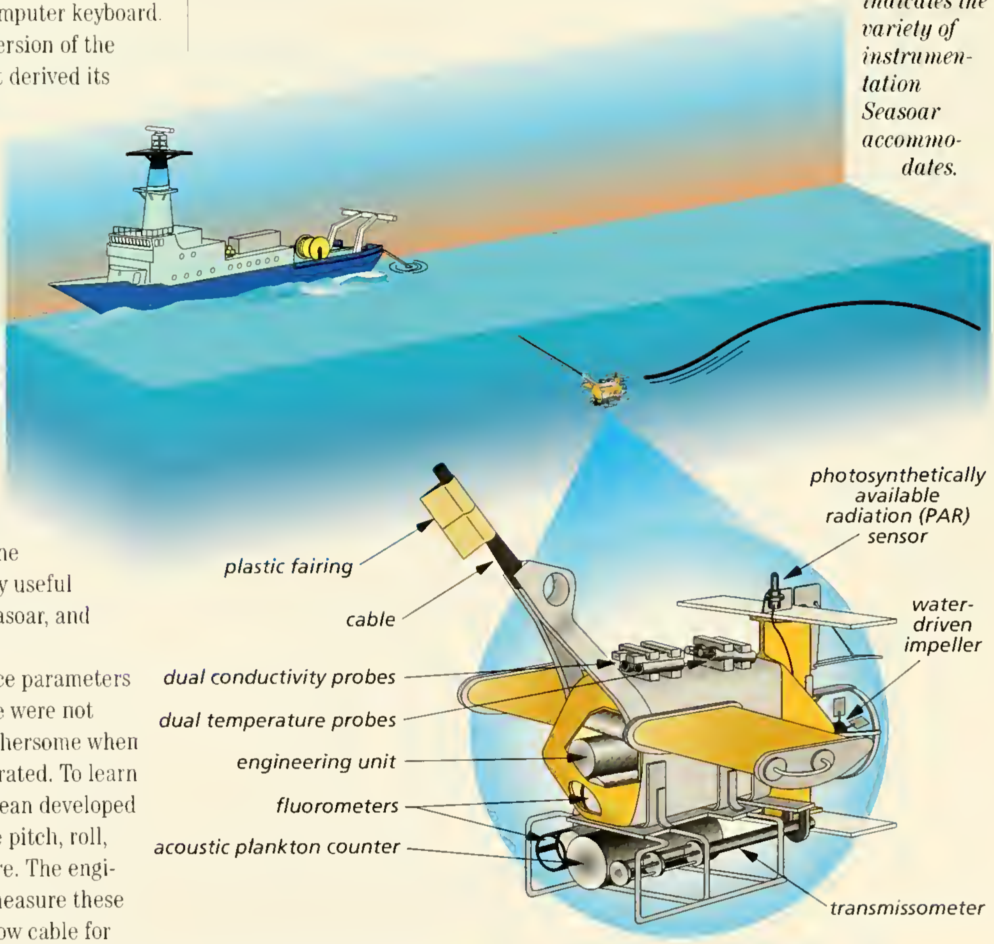
Even with total computer control, we still use a paper chart recorder typical of the type that has been used in oceanography for decades for monitoring Seasoar's flight. This supplement to the digital logbook is particularly useful when noting changes in parameters or reviewing an event that occurred hours or days before.

To date, we have towed Seasoar during six major cruises in the last four years for a total of over 20,000 kilometers (more than half the globe's circumference!) and have collected approximately one billion hydrographic measurements that are contributing to better understanding of the upper ocean.

Frank Bahr's life in oceanography began at Kiel University in his native Germany. He says he got "stuck" in the US when he visited the University of Hawaii as a graduate student. With an MS in oceanography, Frank worked for a while on acoustic Doppler current meters in Hawaii, and then joined the Seasoar project at WHOI in 1991.

When Paul Fucile was 4 years old, his aunt gave him a transistor radio that he took apart. His mother got angry with him, so he put the radio back together—and it worked. Thirty years later, he still takes things apart to see the way they work. Fucile holds a BSEE from Worcester Polytechnic Institute. In his spare time, he collects old German microphones.

Seasoar collects data from the upper 350 meters of the water column in an undulating flight path. Callout shows engineering features of the instrument and indicates the variety of instrumentation Seasoar accommodates.



JAYNE DOUCETTE

Analyzing Rocks with Microbeams

WHOI's Ion Probe Laboratory

Nobumichi Shimizu
Senior Scientist, Geology & Geophysics Department

Study of geologic processes is often detective work. Rocks and minerals are end-products that contain detailed records of when, how, and where the geological processes that formed them occurred. The major objective of petrology and geochemistry is to read these records and understand how the earth works.

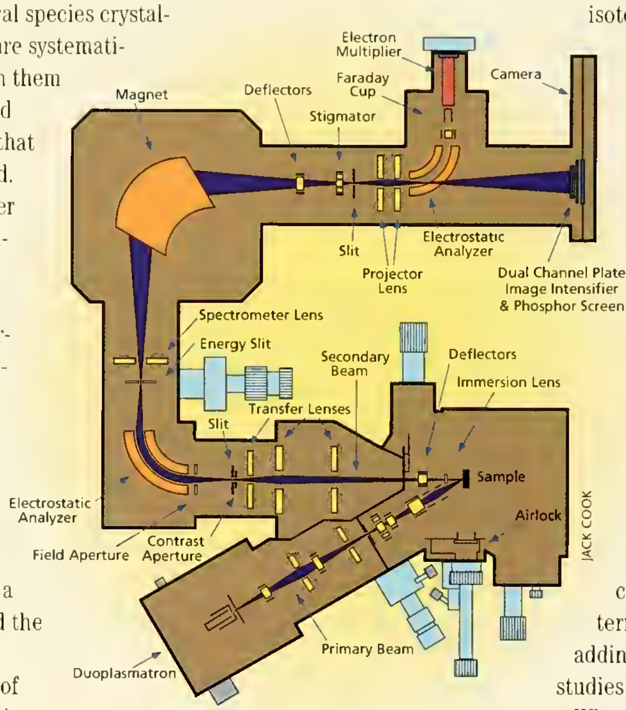
Important clues for this detective work are called natural tracers. Radiogenic isotopes (isotopes produced by radioactive decay of parent isotopes—lead 206 produced by decay of uranium 238, for instance) are important natural tracers for determining *when* rocks were formed. Abundances of elements that exist in very small or "trace" quantities, called trace elements, are often sensitive indicators of *how* minerals crystallize. When two or more mineral species crystallize in a rock, elements are systematically distributed between them according to pressure and temperature conditions that tell us *where* they formed. By combining these tracer data, scientists can quantitatively document the workings of geologic processes, and our understanding of Earth's evolution progresses.

Chemical and isotopic analyses of minerals and rocks yield crucial tracer data. In some cases, an important tracer is a component of a rare mineral species, and the analytical work involves painstaking purification of the specific mineral species, followed by lengthy chemical procedures. In addition, most rocks form under evolving conditions that result in chemically inhomogeneous minerals. Then, even perfectly purified minerals provide only "averaged out" tracer signals that can be misleading.

These practical difficulties are removed with analytical techniques that use microbeams to investigate individual mineral grains within a rock sample without removing the grains themselves (which can destroy the textures in which they occur). For instance, bombarding a mineral with a beam of electrons produces X-rays, whose spectra contain information about the kinds and amounts of elements present in the bombarded area. This technique revolutionized petrology in the early 1960s when it became available in an instrument called an electron probe microanalyzer. Another microbeam technique involves bombarding a mineral specimen with a beam of ions. Because ions are much heavier than electrons, ion-beam bombardment induces cascades of atom collisions within a sample. As a result, atoms and molecules are ejected, some as ions. This process is called sputtering. An ion probe has two parts: a focused ion-beam source for sputtering ions from a small-volume sample, and a mass spectrometer for analyzing sputtered ions. Compared with an electron probe, an ion probe has excellent sensitivity for trace-element analysis and the capability to determine isotopic composition. This enables scientists to determine natural tracer characteristics directly on polished-rock samples, and eliminates the tedious work of separating out the minerals as well as the lengthy chemical procedures that follow.

Because the minerals in a rock display various textures according to how they crystallize, microbeam techniques applied to specific mineral grains while still in place within a rock sample can combine tracer characteristics and mineral textures, adding another dimension to studies of geologic processes.

What roles does an ion probe play in oceanographic research? In "hard-rock" marine geochemistry/petrology, the fundamental questions about mid-ocean ridge magmatism concern where melting begins, how it proceeds, and how melts migrate upwards toward the ocean floor. The WHOI ion probe has proven to be a powerful tool for answering these questions. For instance, Kevin Johnson, a former MIT/WHOI Joint Program student (now at the Bishop Museum in Honolulu), worked with Henry Dick and the author on abyssal peridotites dredged from fracture zones on the Southwest Indian Ridge. Ion probe analysis of these rocks, which remain after melting of up-



CAMECA ims 3f ION MICROPROBE

A horizontal section of an ion microprobe along the axis of the ion beam paths. The primary ion beam produced in the Duoplasmatron (lower left) is focused on the sample and sputters a secondary ion beam. This secondary beam is accelerated into a double-focusing mass spectrometer with an electrostatic analyzer (center left) and a magnet (upper left), and mass-analyzed ions are detected by an electron multiplier (top), or form an image on a dual-channel plate and phosphor screen (upper right).

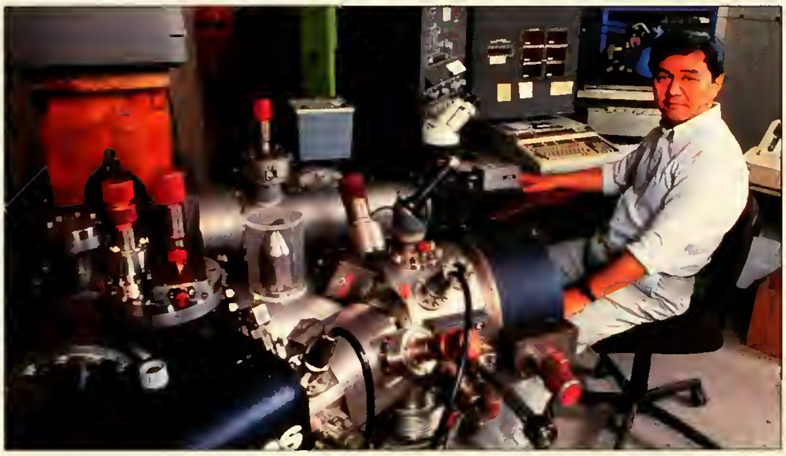
welling mantle beneath mid-ocean ridges, determined abundances of trace elements (particularly rare-earth elements or "lanthanides") in a mineral called diopside, and demonstrated that the melting process operating beneath mid-ocean ridges is akin to "fractional melting," in which a small fraction of melt produced is immediately extracted from the residual mantle. This was the first unequivocal geochemical evidence for identifying the style of the melting process. Extensive hydrothermal alteration and very small amounts of diopside in these rocks had made geochemical studies of abyssal peridotites prohibitively difficult with conventional techniques. The difficulties were successfully overcome by the ion probe's microbeam capability. Determinations of trace-element abundances in olivine-hosted melt inclusions—droplets of melt less than 1 millimeter across entrapped in olivine crystals as beads of glass—provided important clues that place the depths of melting and melt extraction at greater than 80 kilometers. Furthermore, ongoing studies of the upper mantle section of the Oman ophiolite (95 million-year-old oceanic crust and mantle found in an Oman land mass) by Peter Kelemen and the author are providing definitive answers to how mid-ocean ridge magmas migrate and react with mantle peridotite.

The ion probe's usefulness extends far beyond hard-rock geochemistry. For example, recent work by Stan Hart and Anne Cohen demonstrates that strontium/calcium and barium/calcium ratios measured with the instrument in various growth zones of corals present detailed time-series data on seawater temperature and nutrient fluctuations, strongly suggesting a possibility of detecting past El Niño and El Niño-Southern Oscillation events, and determining whether El Niño events in different oceans are derived from a single cause or are separate events. Observations of this type, easily made with the ion probe, are essential to our understanding of mechanisms and time scales of seawater temperature change and their relation to climate change.

The ion probe is beginning to serve marine biology as well. Kevin Friedland of the National Marine Fisheries Service Woods Hole laboratory recently initiated an ion-probe study of trace elements in salmon otoliths (ear bones). Preliminary results suggest that abundances of some elements in otoliths vary systematically as individual fishes grow, offering time-series data that reflect genetic, physiological, and environmental factors. This type of observation has potential for fish-stock identification, analysis of the maturation potential of grilse (young salmon on their first return to fresh water), and possibly the chemistry of fish navigation at sea.

The WHOI ion probe lab is an outgrowth of the MIT-Brown-Harvard regional facility operated at MIT for 12 years (1978 to 1990). The facility was reorganized as the Northeast Regional Ion Microprobe Facility (NERIMF), a consortium effort involving WHOI, MIT, Brown University, Rensselaer Polytechnic Institute, the Lamont-Doherty Earth Observatory, and the American Museum of Natural History. The lab is used each year by more than 50 scientists from many disciplines working across the US and beyond. Among 15 earth-science ion probe labs worldwide, the WHOI facility uses the oldest and yet the most productive instrument (a Cameca IMS 3f, vintage 1978).

With major funding from the Kresge Foundation, an additional grant from the Cecil and Ida Green Foundation, support from the National Science Foundation, and contributions from consortium members, the facility is now expecting a new-generation instrument (a Cameca IMS 1270) to be delivered by the end of 1995. This instrument is designed to have higher mass resolution, higher transmission, and better electronics and computer systems relative to the IMS 3f; it will significantly expand our analytical capabilities and scientific goals.


TOM KLEINDINST

Nobu Shimizu at the Cameca IMS 3f in the ion probe lab. A new generation ion probe is scheduled for delivery by the end of the year.

The analyses we make now will be made with more precision and speed and better spatial resolution, and elements now beyond detection limits will be accessible. Determination of the ages of uranium- and thorium-rich minerals based on the uranium-lead and thorium-lead decay systems without separation will become possible, and high-precision analyses of isotopic ratios of oxygen and carbon will allow us to obtain the better-constrained time-series data essential to paleoceanography and climate-change studies.

The real work of oceanographers who collect samples from the oceans (creatures, sediments, rocks) for chemical and isotopic analysis begins when the ship comes in. The analytical capabilities of shore-based facilities are critically important to the quality of their science. The WHOI ion probe facility has been providing unique analytical opportunities for scientists in diverse disciplines, and its roles will continue to increase as microbeam geochemical analysis becomes more important in our understanding of the workings of geologic processes and in expanding oceanography's horizons.

Articles on the work discussed in this article have been published in the Journal of Geophysical Research *and* Mineralogical Magazine, *and a* Nature *article is in press for 1995.*

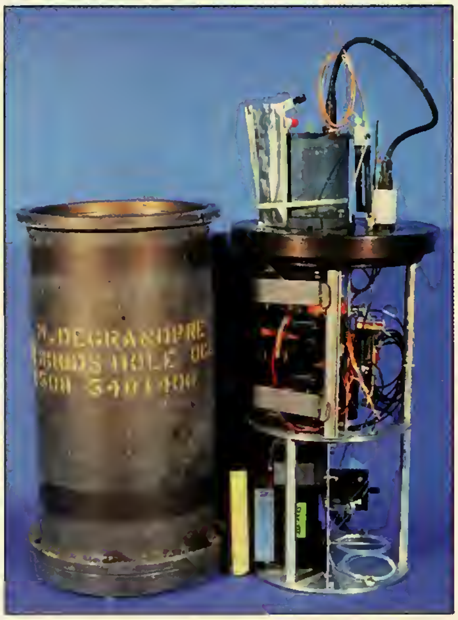
After a 17-year global migration from his native Tokyo to Washington, DC, then Paris, France, then Cambridge, Massachusetts, Nobu Shimizu joined the WHOI staff in 1988. He is the "guru of ion probology" in earth sciences, and a practicing therapist in various relationships (mostly geochemical).

Chemical Sensors in Marine Science

Michael D. DeGrandpre
Research Associate, Marine Chemistry & Geochemistry Department
Richard G. J. Bellerby
Postdoctoral Investigator, Marine Chemistry & Geochemistry Department

Chemists might debate the definition of a chemical sensor, but within the context of this article we consider a chemical sensor to be an instrument or probe that can be placed directly into the process under study to measure a bulk chemical property (such as salinity), specific chemical compound, or an element. Measurements made inside the process are often referred to as "in situ" measurements as opposed to the traditional approach of removing a sample for later laboratory analysis. In situ chemical measurements provide important advantages over sampling when studying almost any chemical process. The advantages, which will be described in more detail later, include fewer sampling artifacts, continuous and immediate (often called real-time) information, better spatial resolution, remote and unattended operation, and lower costs. These benefits have made in situ chemical sensors very popular in industrial chemical manufacturing, biomedical monitoring, and environmental sciences.

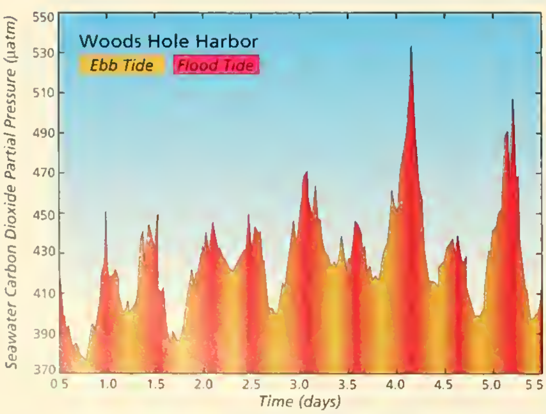
Many of the same chemical measurement challenges familiar to the chemical industry are encountered in the marine sciences. In fact, the ocean might be considered a huge reaction vessel, with seawater carrying nutrients, dissolved gases, organic compounds and trace elements as feedstock for biological and geochemical processes. An industrial approach would place instruments "on-line" in as many places as possible, and use the information obtained to generate predictive models that describe the process's behavior under varying operating conditions. But how can we study the expansive, highly dynamic, heterogeneous ocean in sufficient detail to understand biogeochemical processes? Oceanic biogeochemical pathways for many chemical species, particularly those considered important with regard to climate change, such as carbon and sulfur, have been subject to significant scrutiny through conventional ship-based sampling. Seawater sampling has evolved from bucket collection to the more sophisticated sampling-bottle rosette that accompanies a ship's CTD (Conductivity, Temperature, Depth) profiler. Sediment samples are obtained by a variety of mechanical devices such as grabs and box corers. Yet even with intensive sampling, chemical data remain sparse in space and time relative to the large variability of most biogeochemically important chemical species. Ship-based surveys are biased toward more accessible (mid-latitude) regions and fair weather, and, due to their sporadic nature, they often miss important events such as phytoplankton blooms. In addition, samples can change from their original state during the period between collection and analysis. To study the oceans more effectively, chemical species need to be measured in situ on towed platforms, remotely operated or autonomous vehicles, and moorings.



TOM KLEINDINST

The submersible autonomous moored instrument for measuring seawater carbon dioxide developed at WHOI by Mike DeGrandpre, Terry Hammar, and Steve Smith. The photo shows the pressure housing and internal electronics, detector, data logger, and batteries. The sensor portion is located on the pressure housing end-cap.

A time-series record of carbon dioxide measured using the in situ carbon dioxide sensor shown at right. The sensor was placed in 5 meters of water off the WHOI pier. The carbon-dioxide record is highly variable due to photosynthesis and respiration in the productive shallow waters around Woods Hole.



JAYNE DOUCETTE

One of the first chemical sensors developed for oceanography, the conductivity cell (see *Oceanus*, Spring 1991), has had an enormous impact not in marine chemistry but in the field of physical oceanography. Conductivity instruments can now be moored and towed to measure seawater salinity, providing great insights into ocean circulation. What tools do marine chemists have that are capable of directly probing the ocean? Until recently, most chemical measurements were chained to the laboratory bench because adapting them as in situ sensors posed serious technical challenges. Typically, a sensor must accurately resolve very small

changes at low concentrations, selectively detect chemical species in the complex ionic seawater matrix, operate at low power, and be reliable, small, and inexpensive. Integrating chemical protocols and oceanographic instrument design has been problematic. Additionally, the time frames of funding and that required to make an instrument really work are often incompatible. However, through a combination of new technologies and considerable determination on the part of a few researchers, there is now a suite of proven in situ techniques. We have summarized many of them in the table below along with their operating platforms. The table also identifies the chemicals for which measurements have been demonstrated over the last four years and the sensors that are commercially available.

Most successful sensor-development efforts in marine chemistry have been driven by applications that could not be effectively studied using traditional methods. Scientists who study benthic (ocean floor) biogeochemical processes, especially in the deep ocean, have long been faced with sampling difficulties. As core samples are retrieved from the depths, they usually undergo large changes in temperature and pressure that alter the chemical processes at work, introducing sampling artifacts. For this reason, benthic researchers have pioneered the use of microelectrodes that can measure chemical properties, such as oxygen, carbon dioxide, and pH, in situ with very good spatial resolution (less than 1 millimeter). These sensors, deployed on benthic landers, are automatically pushed into the sediment to detect chemical gradients. Benthic landers may reside on the seafloor for months at a time, providing a nearly continuous record of biogeochemical processes. It is important to note that only oxygen measurements even approach what could be considered routine; microelectrodes for other measurements are difficult to fabricate and often do not operate reliably at the high pressures and low temperatures characteristic of the deep ocean.

In the surface ocean there is much interest in understanding the variability of dissolved gases such as oxygen and carbon dioxide. Biological production, gas exchange from wave breaking, and upwelling are just a few of the processes that contribute to the highly dynamic nature of these gases at the air-sea interface. Their variability and complexity make it vital to measure carbon dioxide and oxygen frequently and over long time periods. In addition, sampling can be difficult because of the potential exchange of gases between a sample and the atmosphere. Oxygen polarographic electrodes have been used to study dissolved oxygen from moorings, CTD rosettes, and towed vehicles, and they are among the few chemical sensors commercially produced for oceanographic research.

Over the past few years, a carbon-dioxide sensor, which uses a dye that changes color in response to carbon dioxide, has been developed in one of the author's labs (DeGrandpre) to operate autonomously on moorings. A carbon dioxide time series collected with the sensor submerged in Woods Hole Harbor shows highly dynamic carbon dioxide signals due to tidal flows from productive shallow waters during ebb tide (see figure opposite). It is not difficult to imagine that intermittent sampling would not effectively capture the large, rapid changes in carbon dioxide characteristics of these waters. In the future, widespread deployment of the oxygen and carbon dioxide sensors on ocean moorings will provide valuable information for understanding the marine carbon cycle.

Nutrients (such as nitrate, phosphate, silicate, and ammonium) and trace metals (iron and manganese, for example) can also be highly variable due to biological processes and terrestrial and hydrothermal inputs. Thanks largely to the efforts of Ken Johnson (Moss Landing Marine Lab and Monterey Bay Aquarium Research Institute—MBARI), many of these chemical species can be measured in situ. He has developed Submersible Chemical ANalyzers (known as Scanners) that can be deployed on CTD rosettes, submersibles, and towed vehicles. Nitrate has been measured directly in the water column using submersible analyzers on CTDs, and an autonomous nitrate analyzer has been developed for use on moorings by Hans Jannasch*, Ken Johnson, and colleagues at MBARI. These autonomous, in situ sensors provide fine-scale resolution and long-term time series of nitrate in the water column to help understand the variability of this important phytoplankton nutrient. In situ analyzers for phosphate, silicate, and a suite

* WHOI Note: Hans Jannasch is the son of WHOI microbiologist Holger Jannasch

MIKE DEGRANDPRE

A mooring equipped with carbon dioxide and oxygen sensors is prepared for launch off the North Carolina coast aboard R/V Cape Hatteras *(Duke/UNC Oceanographic Consortium).*

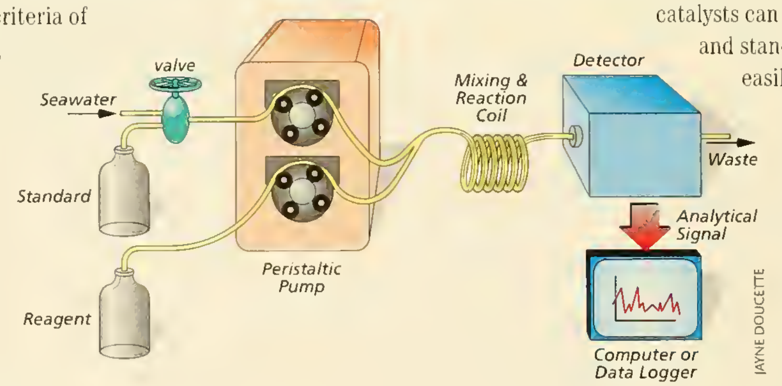
Table shows proven in situ chemical techniques and their platforms.

Chemical Class	CTD Rosette	Mooring	Submersibles & Towed Vehicles	Benthic Lander
Bulk Chemical Property				
Salinity	✓†	✓†	✓†	✓†
Colored Dissolved Organic Matter	✓*†	✓*†		
Dissolved Gases				
Oxygen	✓†	✓†	✓†	✓
Carbon Dioxide		✓*		
Total Gas Tension		✓*		
Nutrients				
Nitrate	✓	✓*		
Phosphate			✓*	
Silicate	✓		✓	
Other				
Manganese	✓*		✓*	
Iron			✓*	
Sulfide			✓	
pH	✓†	✓		✓*

✓ field tested in situ sensors † commercially available * developed within last 4 years

of trace metals are used successfully in the study of hydrothermal vents. The plumes surrounding hydrothermal vents are highly heterogeneous and transient, and are difficult to sample with conventional methods. Researchers have provided detailed maps of chemical distributions by towing an array of chemical analyzers through the plumes (Gary Massoth and colleagues at the Pacific Marine Environmental Laboratory of the National Oceanic and Atmospheric Administration). In another plume study, a gamma ray detector was placed in situ to measure the flow of radioisotopes directly from a hydrothermal vent (David Kadko, University of Miami).

The continuous flow analyzer has been successfully used to measure many chemical species and may offer the most promising design for future in situ chemical sensors.



All the sensors discussed meet (to some degree) the criteria of simplicity, stability, selectivity, power, size, and cost for in situ chemical measurements. Ensuring the stability (long-term accuracy) of in situ chemical measurements is one of the most difficult obstacles. All chemical sensors tend to have some inherent drift that must be corrected through in situ calibrations or other analytical "tricks." For example, oxygen microelectrode measurements in benthic chambers (incubators that trap water over the sediment on the ocean floor) are referenced to constant bottom-water oxygen outside of the chamber. The ratio corrects for drift in the electrode, providing an accurate record of the decrease in chamber oxygen over time (figure below). Similarly, to measure water-column carbon dioxide, our sensor uses a ratio of the indicator (dye) optical absorbances that corrects for drift in the detection electronics and light source. We also isolate the indicator in an inert, gas-impermeable bag and flush it out for each measurement. By renewing the indicator and using absorbance ratios, stable measurements of seawater carbon dioxide have been achieved for month-long periods.

The continuous flow analyzer (Scanner) uses "standard" solutions (containing known quantities of the substances being measured) to calibrate the analyzer in situ. In these types of analyzers, seawater and reagents are pumped together (figure above) into a mixing coil and then to the detection system. The reagents selectively react with chemical species, most commonly forming, depending upon the analyzer, a colored or fluorescent product. A standard is introduced periodically to calibrate the analyzer. The in situ calibration takes into account the change in response due to temperature, hydrostatic pressure, and other environmental factors.

Our understanding of marine biogeochemical processes will remain limited if we rely solely upon ship-based studies. In the near future, a greater number of chemical measurements will be made with moored sensors. The generic continuous flow analyzer may be the most promising approach for many oceanographic applications. It can be configured with a wide variety of optical and electrochemical detectors, preconcentrators (resins that preconcentrate the chemical species) and catalysts can be put in-line, and standards can be easily introduced for calibrations. Continuous flow analyzers developed for ship-based deployments have high reagent consumption and use peristaltic pumps that require periodic maintenance. Recent technological advances now provide a variety of miniature, low-power, reliable valves and pumps, including osmotic pumps used by Hans Jannasch, that require no power. These advancements should eliminate the need for peristaltic pumps and facilitate miniaturization of the analyzers to reduce reagent consumption. Although each application presents significant technical challenges, many of the core ship-based measurements of nutrients, trace metals, dissolved gases, and inorganic and organic carbon may well be converted to in situ sensors using currently available technology. To successfully exploit this opportunity will typically require a three- to four-year effort from a group of skilled researchers and engineers, including a nearly full-time commitment from an individual with a vested scientific interest in making the sensor work. An important additional step will be to encourage commercialization of new autonomous chemical sensors to make them available to the entire oceanographic community.

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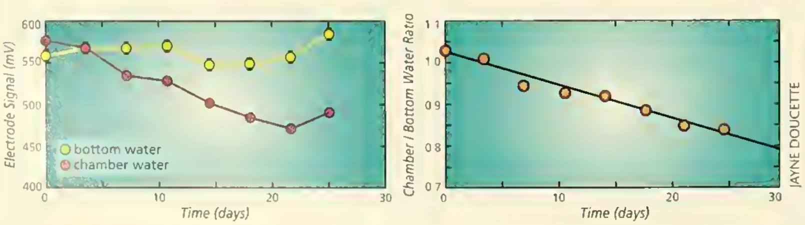
Since earning his PhD in analytical chemistry in 1990 from the University of Washington, Mike DeGrandpre has striven to move chemical analyses from the beaker into the ocean, motivated by the idea that "the open ocean is a nice place to visit but I wouldn't want to live there." Richard Bellerby took a postdoctoral position at WHOI following completion of a PhD in marine chemistry at the United Kingdom's University of Plymouth and The Plymouth Marine Laboratory in 1994. He is researching the application of spectroscopy to remotely characterize the marine carbon-dioxide system.

To accurately record oxygen consumption at the ocean floor, oxygen electrode signals are recorded both from inside and outside the benthic chamber (plot on left). Since the bottom-water oxygen outside the chamber does not change, this signal is used as a reference to correct for unwanted drift in the electrode signal (plot on right). These data were collected in 4,500 meters of water off Bermuda (courtesy of Fred Sayles, WHOI).



DSV *Alvin*

For a rousing tale of the deep submergence vehicle *Alvin*'s first 25 years, readers may want to locate a copy of *Waterbaby, the Story of Alvin* by Victoria Kaharl (Oxford University Press, 1990). The book begins with the observation that "Since very early times, at least three hundred years before Christ, humankind has used all kinds of contraptions—suits of armor and animal skins, kettles or diving bells, leather hoods, snorkels, nose clips—to get beneath the waves. It was in Leonardo da Vinci's time when the first practical-looking underwater boats began to appear." Stealth was the idea behind virtually all early submersibles, and, according to *Waterbaby*, "With few exceptions, war was the motivation behind the evolution of the submarine."

It was in the mid 1950s that scientists began to discuss the potential of submersible research in the deep sea. There are a number of heroes, many of them in Navy uniform, in the story that takes this concept from idea to reality. The person we at WHOI know best is the late Allyn Vine, who lobbied tirelessly for the idea. As a result of his and others' efforts, the deep submergence vehicle *Alvin* was built in the early 1960s, when enthusiasm for "man in the sea" was ascending, by the US Navy so that scientists could make direct observations and manipulations in the deep sea. When placed in service at the Woods Hole Oceanographic Institution in 1964 with a steel personnel sphere, *Alvin* could take three people as deep as 1,868 meters (6,000 feet) on dives that lasted 6 to 10 hours. The sub proved its worth in an unexpected way in 1966 by assisting in the search for and recovery of a US hydrogen bomb accidently lost in 780 meters of water off the coast of Spain. From then until the early 1970s, *Alvin* supported science programs with 60 to 80 dives a year from its catamaran support vessel *Lulu*. When the US Navy built *Sea Cliff* and *Turtle* in the late 1960s for deep-water search-and-retrieval tasks, *Alvin* was used as the model. During a 1972–1973 overhaul, a new titanium personnel sphere was installed in *Alvin* to double the sub's depth capability to 3,658 meters (12,000 feet).

Alvin's 1974 role in Project FAMOUS (French-American Mid-Ocean Undersea Study), along with its French counterparts, *Cyana* and *Archimède*, marked a turning point for broad acceptance of the submersible's role as critical in deep-ocean science. On this expedition to the Mid-Atlantic Ridge, scientists obtained information that confirmed the theory of seafloor spreading. Following that success, *Alvin*'s ultilization rate steadily increased, accompanied by continuous technological improvements to the vehicle. A series of dives to the Galàpagos Rift in 1977 brought the startling discovery of deep-sea hydrothermal vents and the communities of unusual animals that surround them. As a result of continuing investigations at the mid-ocean ridges and in other areas, the deep-diving submersible has become a valued and respected workhorse of the oceanographic research community. Today *Alvin* routinely makes between 150 and 200 dives each year. Its depth capability was extended to 4,000 meters (13,900 feet) in 1978 and to 4,500 meters (14,764 feet) in 1994.

With the advent of remotely operated and autonomous vehicles over the last decade, some have speculated that the crewed submersible's star is declining. However, it appears at this point that these vehicles will be working with rather than replacing vehicles like *Alvin*. The sub quietly observed its 30th birthday in 1994, having logged its 2,772nd dive. In 1995, the demand for humans to probe the depths of seas in person is robust.

—*Barrie B. Walden and Vicky Cullen*


CRAIG DICKSON

DSV Alvin *is lifted from the water by parent ship R/V* Atlantis II *following a dive.*

For information about how Alvin *and other deep-diving research vehicles fit into the submersible history of the last three decades, readers are referred to "The New Submersibles" by Barrie B. Walden in the* Encyclopedia Britannica's 1995 Yearbook of Science and the Future.

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